VOL. 8 No. 9, p. 257-288 SEPTEMBER 1946

Philips Technical Review

DEALING WITH TECHNICAL PROBLEMS
RELATING TO THE PRODUCTS, PROCESSES AND INVESTIGATIONS OF
N.V. PHILIPS' GLOEILAMPENFABRIEKEN

EDITED BY THE RESEARCH LABORATORY OF N.V. PHILIPS' GLOEILAMPENFABRIEKEN, EINDHOVEN, HOLLAND

THE MULTIREFLECTION TUBE
A NEW OSCILLATOR FOR VERY SHORT WAVES

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The multi-reflection tube is a reflex oscillator differing essentially in construction and functioning from the ordinary reflex oscillators. With the latter effective use can be made of only one reflection in the space between the modulator system and the repeller electrode. In the multi-reflection tube, on the other hand, the electrons execute a pendulum motion about the modulator system with a constant periodic time, so that each time they pass the modulator system they induce a current of the correct phase, which results in a much higher efficiency than that of the usual reflex oscillators. This constancy of the periodic time is achieved by a suitable choice of the potential gradient between the modulator system and the repeller electrode and cathode respectively. The multi-reflection tube can be used for pulsating operation as well as for continuous wave operation.

Among the modern oscillators the magnetron and velocity-modulated tubes occupy the most important places in the field of decimetre and centimetre waves. Velocity modulated tubes have recently been discussed in detail in this periodical[1]); their action is based on the electrons first being modulated in velocity and the velocity-modulation then being converted into a density modulation due to the electrons overtaking each other in a field-free space. In the so-called reflex oscillators the effect of the electrons overtaking each other also plays an essential part, but the conversion of velocity-modulation into density-modulation no longer takes place in a field-free space, the electrons being "reflected" by an electrostatic field back to the modulating system that modulated them in velocity. The principle of the reflex oscillator will be compared with that of the "ordinary" velocity modulated tube in more detail farther on. Here it is to be remarked that one great objection to the reflex oscillators hitherto known was their low efficiency. A new reflex oscillator, the "multi-reflection tube", has now been developed by Philips, the principle and construction of which will be described in this article. This new reflex oscillator has a high efficiency, mainly due to a suitable choice of the above-mentioned electrostatic field.

Principle of the reflex oscillator

In order to show clearly the fundamental difference between the action of the reflex oscillator and that of the ordinary velocity-modulated tube we shall outline the action of the latter with reference to

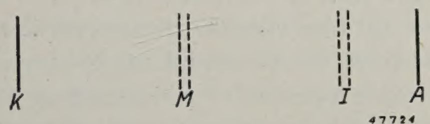


Fig. 1. Diagram showing the principle of a velocity modulated tube. K cathode, M grids of the modulator between which the electrons are modulated in velocity by an A.C. voltage. Between M and I is a field-free space for overtaking, in which velocity-modulation is converted into density-modulation; I inductor to which density-modulated electrons give off their high-frequency energy.

fig. 1; for all details we refer to the article already mentioned [1]). The electrons of a beam emitted from the cathode are first brought to a high velocity, which is the same for all. Between the grids of the "modulator" there is an A.C. voltage, and here the electrons undergo small variations in velocity, the magnitude of which depends on the moment at which the electrons enter the modulator. Next the electrons enter a space that is free of field, the "drift space". Because of the variations

[1]) F. M. Penning, Velocity-modulation Valves, Philips Techn. Rev. 8, 214, 1946.

in velocity the electrons which started later will be able to overtake in this space those which started sooner, this resulting in variations in density along the beam. At a point where the density reaches a high value there are the grids of the induction system, the "inductor". Here, owing to the fluctuations of density, high-frequency alternating currents are induced [2]). By applying a feedback from the inductor to the modulator an oscillating system is obtained.

The conversion of velocity-modulation into density-modulation can be brought about otherwise than by causing the electrons leaving the modulator to overtake each other in a field-free space. In the reflex oscillators this is accomplished, as already stated, by causing the electrons to strike up against a retarding electrostatic field, so that they are ultimately thrown back upon the modulator (*cf. fig. 2*), obviously resulting in density modulation.

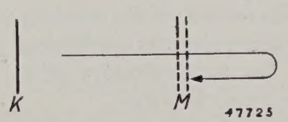


Fig. 2. Diagram showing the principle of a reflex oscillator. *K* cathode; *M* modulator which here also plays the part of an inductor. To the right of *M* is an electrostatic retarding field which causes the electrons to reverse their direction. (How the retarding field is obtained is not indicated in the figure.) Since the transit time of the electrons in the retarding field depends upon their initial velocity, and this is modulated by *M*, the electron current returning to *M* is modulated in density. By a proper choice of the phase difference between this current and the A.C. voltage, the high-frequency energy can be made to be given off to *M*.

The transit time of an electron in the retarding field — *i.e.* the time that the electron takes to travel from and back to the modulator — depends not only on the properties of the retarding field but also on the velocity with which the electron leaves the modulator. The electrons which leave the modulator at equal intervals but at different velocities will therefore in general arrive back at the modulator at unequal intervals, which means that the originally constant current density is in fact converted into a time-dependent current density, and if the modulating voltage is periodic that current density will be a periodic function of the time.

Now if it is desired to use this method of converting velocity-modulation into density-modulation to obtain an oscillator, it is only necessary to arrange for the modulator to act the part of inductor for the returning density-modulated electrons. This is accomplished by a suitable choice of the phase difference between the modulating voltage and the current density of the electrons returning to the modulator.

The fundamental similarity with the ordinary velocity-modulated tubes thus consists in the fact that, by means of a relatively long transit time, either in a field-free space or in a retarding field, the electrons are given the opportunity of converting their velocity-modulation into density-modulation. The fundamental difference consists in the modulator and the inductor of an ordinary velocity-modulated tube having become identical. Henceforward this arrangement, which in reflex oscillators provides both for the velocity-modulation of the electrons and for the induction of their high-frequency energy, will be called the "modulator system" (*cf.* footnote [2])).

Reflex oscillator with a linear retarding field

In the foregoing our remarks have been confined to generalities and no precise definition has yet been given of the kind of retarding field used in the existing reflex oscillators. In point of fact, what has been used almost exclusively so far is a linear retarding field, by which is meant the simple situation shown diagrammatically in *fig. 3*. Here the retarding field is formed by introducing at some distance behind the modulator system a "repeller electrode" at a potential a few hundred volts lower than the cathode potential: the potential variation between the modulator system and the repeller electrode is then linear, at least if space-charge effects are to be disregarded, which will usually be the case here.

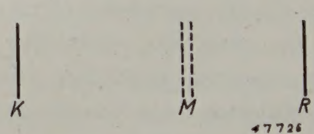


Fig. 3. Diagram showing the principle of a reflex oscillator with linear retarding field. *K* cathode; *M* grids of the modulator system (which plays both the part of modulator and of inductor); *R* repeller electrode to which a voltage is applied lower than that of the cathode. The variation of potential between *M* and *R* is linear, except for possible space-charge effects.

In a reflex oscillator with a linear retarding field an electron moves in the retarding field like a ball thrown vertically into the air (we disregard

[2]) In itself the action of the inductor is nothing else than that of a second modulator, the only difference being that the density of the electron beam when passing through the first modulator is homogeneous and inhomogeneous when passing the second.
As a consequence the change in the kinetic energy of the electrons in the first case is on an average zero per cycle, whilst in the second case this variation per cycle is negative, so that a surplus of energy is taken up by the inductor.

space charge and air resistance). If v is the velocity with which the electron coming from the cathode reaches the modulator system and Δv is the (positive or negative) velocity modulation which the electron thereby undergoes, its transit time in the retarding field is

$$t_l \text{ proportional to } v + \Delta v.$$

Therefore the accelerated electrons ($\Delta v > 0$) are overtaken by the retarded electrons ($\Delta v < 0$) which started later, thus just the reverse of the case with the continuously forward-moving electrons in the ordinary velocity-modulated tube, where the transit time from the modulator to the inductor is

$$t_l \text{ proportional to } \frac{1}{v + \Delta v}$$

When $|\Delta v/v| \ll 1$, *i.e.* at small depths of modulation, however, there is a far-reaching analogy between the two types of velocity-modulated tubes, considering that then

$$\frac{1}{v \pm |\Delta v|} \approx v \mp |\Delta v|.$$

This analogy will be more clearly shown in the discussion of the efficiency.

Efficiency of the reflex oscillators

Let us suppose that a reflex oscillator (not necessarily with a linear retarding field) is oscillating. The periodically varying voltage on the modulator system and the current which is induced in it by the density-modulated electron beam will in general contain a number of harmonic components. We assume, however, that the oscillator circuit (for instance a cavity resonator or a Lecher system), of which the modulator system forms a part, is tuned to the fundamental frequency, so that we need only consider the fundamental components of the voltage and of the induced current — with the amplitudes V_1 and I_1 respectively. Further we denote by V_0 the electrostatic voltage of the modulator system with respect to the cathode, and by i_0 the unmodulated electron current emitted by the cathode. Assuming, further, that the induced current is in phase with the voltage, which is the most favourable situation for efficiency, the following expression holds for the efficiency η:

$$\eta = \frac{{}^1/_2\, I_1\, V_1}{i_0\, V_0} \quad \ldots \ldots \quad (1)$$

The same formula also holds for ordinary velocity-modulated tubes, it being understood, of course, that V_1 and I_1 are then the voltage on the inductor and the current induced in it. [3])

In order to obtain a high efficiency it is therefore necessary, according to equation (1), to ensure that the ratios I_1/i_0 and V_1/V_0 are as large as possible.

The maximum value of I_1/i_0 at a small depth of modulation is found to be exactly the same for an ordinary velocity-modulated tube as for the reflex oscillator with a linear retarding field (*cf.* the remark at the end of the previous section), being in both cases equal to twice the maximum of the Bessel function $J_1(x)$, which amounts to 0.58 [1]). Now with an ordinary velocity-modulated tube V_1 can be chosen equal to V_0 (it cannot be chosen larger because the electrons would then be thrown back before they had reached the inductor), so that the maximum efficiency in that case becomes $\eta_{\max} = {}^1/_2 \cdot 1.16 \times 1 = 0.58$.

On the other hand, in the case of the reflex oscillators in general, and thus also those with a linear retarding field, the ratio V_1/V_0 must be smaller than unity, having regard to the starting of the oscillation. The maximum efficiency of a reflex oscillator with a linear retarding field is therefore considerably less than 0.58.

Due to all kinds of incidentical factors, however, which have been disregarded in the derivation of these theoretical maximum efficiencies, in practice the latter are not even approximated. The efficiencies actually attained in practice with ordinary and with reflex velocity-modulated tubes are of the order of 0.2 and 0.1 respectively.

The multi-reflection tube: its principle and efficiency

The objection, just mentioned, of the low value of V_1/V_0 in reflex velocity-modulated tubes can, however, be overcome indirectly, thanks to a factor which so far has been left out of consideration here, namely what happens to the electrons which after reflection have given off part of their kinetic energy to the modulator system. These electrons, of course, first travel farther on in the direction of the cathode, but ultimately they are driven back again to the modulator system. The question then arose whether it might not be possible to improve efficiency by causing the electrons to swing back and forth around the modulator system in such a way that each time they pass through they give off as much of their energy as possible. This was indeed found to be possible and in the multi-reflection tube we

[3]) The efficiency of the ordinary velocity-modulated tube is discussed in detail in the article already referred to [1]). The readers' attention is called to the fact that in that article our quantities V_1 and I_1 are denoted by V_2 and I_2 respectively.

have a practical realization of just such a possibility.

Let us consider this question somewhat more closely. Each time it passes through an electron gives off to the modulator system an amount of energy equal to $eV_1 \sin(2\pi t_1/T)$, where e is its charge, T the periodic time of the voltage and t_1 the moment of passage. The factor V_1/V_0 in formula (1) for the efficiency is thus equal to the ratio of the maximum energy which an electron can give off to the modulator system in one passage, namely eV_1, to its original energy eV_0. If, now, the electrons are reflected n times by the retarding electrode and the cathode alternately before they disappear from the beam for some reason or other (for instance through divergence), the situation from the point of view of an electron is as if in equation (1) nV_1/V_0 took the place of V_1/V_0. Therefore, if from now on we take I_1 as indicating the amplitude of the induced current when in a reflex tube an electron is reflected only once, then with n reflections the same tube will have an efficiency n times as great:

$$\eta_n = {}^1/_2 \frac{I_1}{i_0} \cdot \frac{nV_1}{V_0}, \quad \ldots \ldots \quad (2)$$

provided the induced current is in phase with the voltage at every passage of the electrons through the modulator system, and its amplitude I_1 remains unaltered. We shall return to this requirement shortly. First we will consider the situation "from the point of view of the modulator system". From that point of view the amplitude of the A.C. voltage does not depend upon the number of reflections, but it is the amplitude of the induced current which becomes n times as large — still under the proviso just mentioned, which might be expressed by writing equation (2) as follows:

$$\eta_n = {}^1/_2 \frac{nI_1}{i_0} \cdot \frac{V_1}{V_0} \quad \ldots \ldots \quad (2a)$$

Now what is implied by the above-mentioned requirement for equation (2) to be valid? Obviously it means in the first place that the periodic time of all the electrons must be the same (in that case once the density modulation has been obtained it will not change during the pendulum motion), and in the second place, that the periodic time must remain constant, in spite of the energy of the electrons diminishing each time they pass through the modulator system (the induced current will then always remain in phase with the voltage). In other words, the condition in question will only be satisfied when the electrons execute a (damped) harmonic pendulum movement about the modulator system with a periodic time that is the same for all electrons. Now it is known that such a motion can only take place when the particle is attracted by a centre of force with a force proportional to the distance; the potential then changes as the square of that distance and the transit time of a particle does not then depend upon its velocity at the position of the centre of force. Thus if the potential to the left and right of the modulator system had a parabolic slope, a density maximum once obtained would travel back and forth without being smoothed out, and would always pass the modulator system in the correct phase. With any other retarding field — especially with the above-mentioned linear retarding field — a density maximum becomes more and more smoothed out during the motion, so that I_1/i_0 soon becomes very small, and there can be no question of an improvement in efficiency.

By introducing the parabolic retarding field, however, we should be rejecting the good with the bad. We wanted to introduce the parabolic field because in that field the density modulation of the electrons dit not change during the motion. In particular, therefore, an electron beam originally unmodulated in density would always remain unmodulated in a parabolic field; in other words I_1/i_0 would not only be small, but it would be exactly zero.

A solution of this dilemma could be sought by dividing the problem into two, namely by first modulating the electron beam in density in some way or other as well as possible, *i.e.* by providing for the largest possible value of I_1/i_0 in equation (2), and then causing the modulated beam to travel back and forth in a parabolic field, so that the factor nV_1/V_0 in equation (2) also assumes a favourable value without the first mentioned factor being changed.

This procedure is now employed in the multi-reflection tube in a remarkable manner, as will be explained in the following.

Let us return for a moment to the case of a single reflection in some retarding field or other; for the present, therefore, we will consider only the variation of the potential to the right of the modulator system (to the left of it is the cathode). For every retarding field there is in general a different maximum value of I_1/i_0, so that two questions arise:

a) with what retarding field do we get the greatest of all those maximum values?
b) How great is that greatest value?

The key to the situation — and on this is based the principle of the multi-reflection tube — is the

following: The optimum retarding field referred to in question a) provides — as we shall soon see — not only that the electrons receive the greatest possible density modulation upon the first reflection, but also that this automatically remains unchanged in the following reflections, provided the field to the left of the modulator system is parabolic.

We shall now investigate question a) more closely. We call i_1 the amplitude of the fundamental component of the modulated electron current at the position of the modulator system after the first reflection, while I_1 was the amplitude of the fundamental component of the induced current. Since $i_1 = I_1$, we may consider i_1/i_0 instead of I_1/i_0. The ratio i_1/i, *i.e.* the density modulation of the electron current, — as we have already stated — is determined entirely by the transit times of the electrons in the retarding field, *i.e.* the time taken by the electrons to travel once back and forth from and to the modulator system. In a given retarding field the transit time is again determined by the velocity with which the electron enters that field. Since this velocity varies periodically with the time t_1 at which the electron enters the retarding field, the transit time is also a periodic function $f(t_1)$ with the same period. The form of the function $f(t_1)$ thereby depends on the retarding field, each $f(t_1)$ corresponding, in general, to a different retarding field. Therefore, for question a) we may substitute the two following questions:

(a_1) With what $f(t_1)$ is i_1/i_0 a maximum?

(a_2) What must be the form of the retarding field in order that the transit time will vary according to the optimum $f(t_1)$ referred to in question (a_1)?

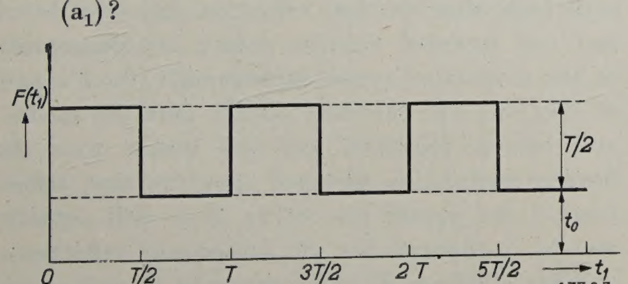


Fig. 4. The transit time $F(t_1)$ of an electron in the optimum retarding field as a function of the time t_1 at which it leaves the grids of the modulator system. The transit time of the electrons retarded by the modulator system is indicated by t_0. The transit time of the accelerated electrons is then $t_0 + T/2$ (T is the period of the A.C. voltage on the modulator system).

We shall not go into the (not very difficult) mathematical considerations which furnish an answer to question (a_1) but will confine ourselves to stating the result. The desired function, which we shall denote by $F(t_1)$, is represented in *fig. 4* [4]). Except for a constant it is given by a so-called square sine with an amplitude amounting to one quarter of its period T (the function $F(t_1)$ having the dimension of a time).

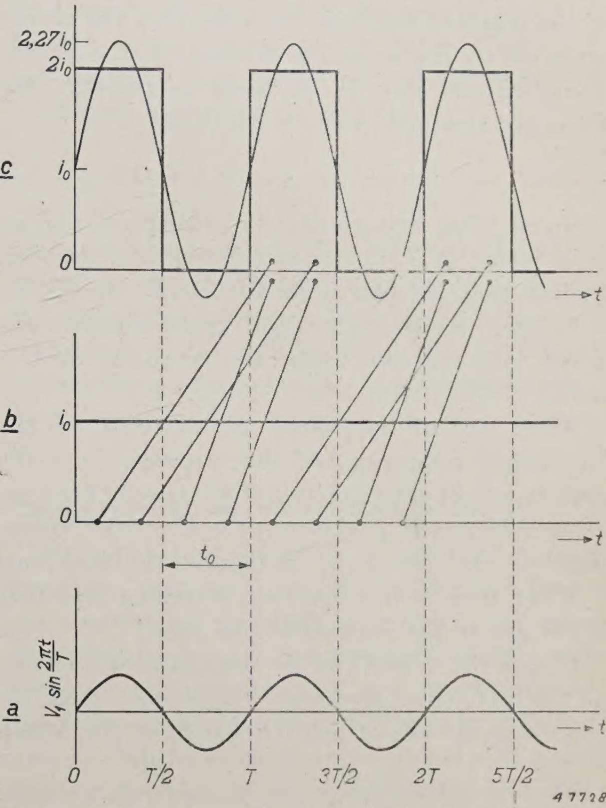


Fig. 5. *a*) A.C. voltage $V_1 \sin(2\pi t/T)$ between the grids of the modulator system as a function of the time.
b) The unmodulated electron current $i = i_0$ as a function of the time; the black dots along the t axis represent the electrons coming from the cathode and reaching the modulator system at equal intervals.
c) The modulated current of the electrons returning to the modulator system as a function of the time, where the transit time function $F(t_1)$ is given by the curve of fig. 4. The heavy line is the total current, the thin line the sum of the time-independent component i_0 and the fundamental component $(4i_0/\pi)\sin(2\pi t/T)$. The black dots above and below the t-axis represent respectively the accelerated and the retarded electrons. It may be seen that at equal intervals during one half of the cycle one accelerated and one retarded electron return simultaneously to the modulator system, and during the other half of the cycle no electrons return.

This has led to the discovery of a very important property of the optimum retarding field. This retarding field must evidently be such that 1) all electrons which are retarded by the modulator system have the same transit time t_0 and 2) all the accelerated electrons also have the same, longer, transit time $t_0 + T/2$. As a result the current density of the electrons returning to the modulator system, as a function of the time, will also be a

[4]) Strictly speaking, this is not the most general form which $F(t_1)$ can have. For our purpose, however, the consideration of the $F(t_1)$ represented in fig. 4 is sufficient.

square sine; it is alternately zero for one half cycle and during the other hal. cycle equal to twice the unmodulated current density.

This can easily be seen from *fig. 5*. The phase difference between the current density and the A.C. voltage is equal to $2\pi/T$ times the transit time t_0 of the retarded electrons. In order that the energy given off by the returning electrons to the modulating system may be as large as possible, the following equation must be satisfied:

$$t_0 = (l + {}^1\!/_2)\,T \quad (l = 0, 1, 2, ..) \quad . \quad . \quad (3)$$

Given $F(t_1)$, it is possible to calculate the maximum value of $I_1/i_0 = i_1/i_0$ referred to in question b), and then is found to be $4/\pi = 1.27$ (*cf.* fig. 5).

In itself this is only a slight improvement compared with the case where the retarding field is linear: $(1.27 - 1.16)/1.16 = 9.5\%$.

What we are interested in, however, is the "optimum" retarding field that corresponds to the specific transit-time function $F(t_1)$, mainly because, as already stated, it allows of the effective employment of the pendulum motion of the electrons.

What, then, is this optimum retarding field that is realized in the multi-reflection tube?

If v_0 is the velocity of an unmodulated electron, all the retarded electrons will reverse their direction to the left of point R (see *fig. 6*), for which

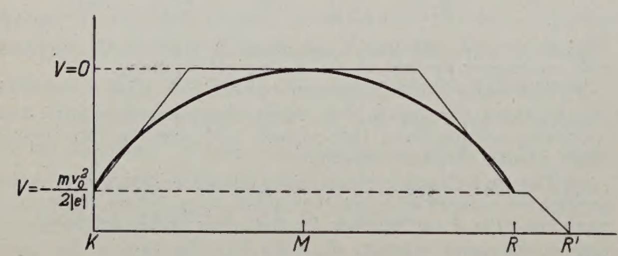


Fig. 6. Variation of the potential V to the left and right of the modulator system M in a multi-reflection tube; K cathode. The parabola is approximated by the three sections of straight line. The potential slope to the right of R (the broken line RR') provides for the accelerated electrons to have a transit time $T/2$ longer than the retarded electrons. The potential difference between M and K (or R) multiplied by the charge e of an electron is equal to the kinetic energy $mv_0^2/2$ of an unmodulated electron.

the voltage, with respect to the modulator system, is $-mv_0^2/2e$ (m and e being the mass and charge of the electron respectively).

It being essential that all retarded electrons shall have the same transit time, the variaton of potential between the modulator system and point R, in accordance with what has alread, been stated, must be parabolic.

If the variation of potential to the left of the modulator system is given by the second symmetrical half of the same parabola, then upon subsequent reflections a retarded electron will pass the modulator system at equal intervals $(k + {}^1\!/_2)T$ (see equation (3)), in spite of the fact that its energy decreases each time. With a multi-reflection valve the parabola in question is approximated by the tripartite line in fig. 6.

The accelerated electrons, *i.e.* the electrons which on leaving the modulator system have a velocity greater than v_0, will on the other hand continue to the right of R. Thanks to this circumstance, the requirement that the accelerated electrons must all have a transit time $T/2$ longer than the retarded electrons can be satisfied in a simple way by choosing a suitable variation for the potential to the right of R: the accelerated electrons are made to "wait" at the right of R. A potential variation which causes the electrons to wait in approximately the desired way — and which is realized in the multi-reflection tube — is represented in fig. 6. The transit time of an accelerated electron in the retarding field to the right of the modulator system is thus equal to

$$(l + {}^1\!/_2)T + {}^1\!/_2T = (l + 1)T,$$

so that such an electron, upon passing the modulator system after the first reflection, loses exactly as much energy as it took up when passing in the opposite direction: thus it enters the space to the left of the modulator system with the velocity v_0. From that moment onwards the originally accelerated electron will behave exactly like an originally retarded electron: upon subsequent reflections it will never be able to enter the region to the right of R. With reference to fig. 5, we have seen that each time after the first reflection one accelerated and one retarded electron return simultaneously to the modulator sytem subsequently. Such a pair of electrons will therefore always pass the modulator system together, and this means that the density modulation obtained upon the first reflection — the square sine of fig. 5 — will actually remain unchanged for all subsequent reflections.

What efficiency is to be expected from a multi-reflection tube on the basis of the theory outlined above? In a multi-reflection tube the optimum retarding field is only approximated. After a certain number of oscillations even in a multi-reflection tube the electrons will become out of phase, or will be removed from the beam by other causes. Actually this falling out of phase occurs quite suddenly: it can be demonstrated that the electrons oscillate with a constant periodic time until their velocity has fallen to about one half, and thus their energy

to a fourth, after which they give off practically no more energy; unless special precautions are taken they might even begin to consume energy. Practically speaking, the current induced in the modulator system is therefore formed — in agreement with equation (2a) — by the superposition of n currents, as represented graphically in *fig. 7*; n here depends upon the value of V_1/V_0.

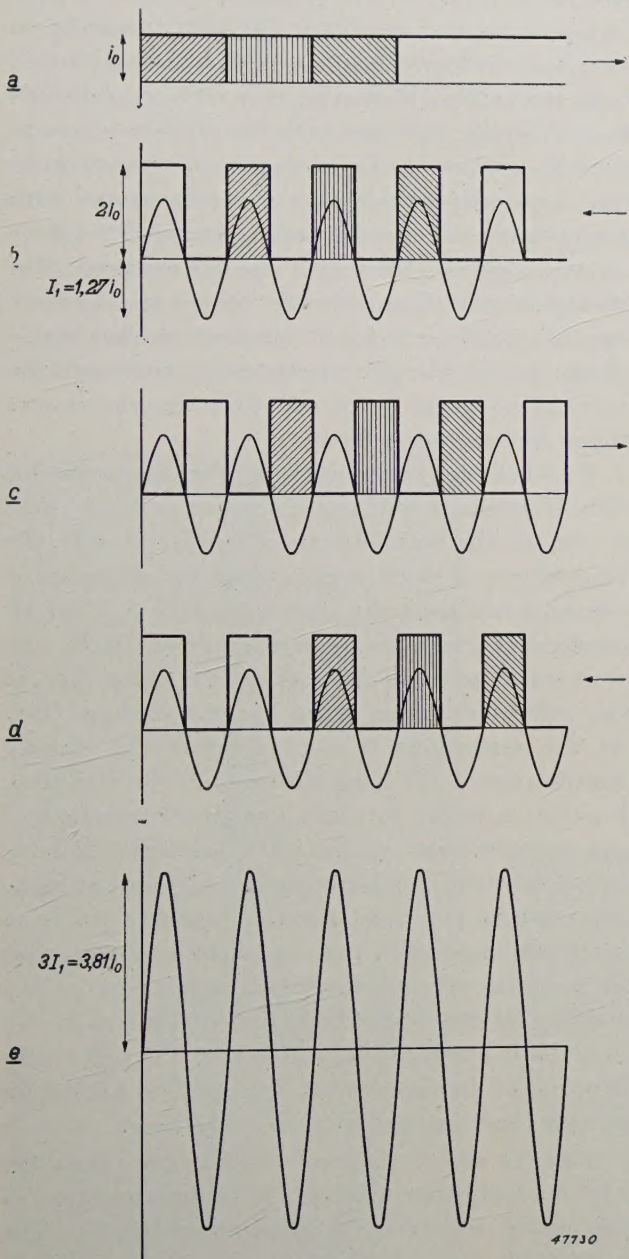


Fig. 7. How the current induced by the electrons is formed. *a*) represents the non-density-modulated current of the electrons passing the modulator system for the first time after leaving the cathode. At each subsequent passage of the electrons in one direction or the other (indicated by arrows) between the grids an A.C. is induced the variation of which with time is represented in *b*), *c*) and *d*); the fundamental component of the induced current is drawn separately in each case. The sum of these currents, *i.e.* the fundamental component of the total induced current, is shown in *e*). Similarly cross-hatched areas represent the currents induced by the same group of electrons.

For a calculation of the efficiency it is to be noted that:

$$\frac{nV_1}{V_0} = \frac{E'-E''}{E'}; \quad \ldots \ldots \quad (4)$$

where E'' is the value of the kinetic energy of the electrons at the moment it falls out of phase, and E' the original kinetic energy. Since $E''/E' = 1/4$ and $I_1 = i_1$, we find for the efficiency, by combining equations (2) and (4):

$$\eta = {}^1/_2 \cdot \frac{i_1}{i_0} \cdot \left(1 - \frac{E''}{E'}\right) = {}^1/_2 \cdot \frac{4}{\pi} \cdot \frac{3}{4} = 0.48 .$$

It is found, however, that some multi-reflection tubes can attain efficiencies up to 50%. Even if the error of measurement were of the order of 4% the result would still be doubtful, because the circuit losses and radiation losses certainly cannot be ignored. We shall revert to this surprising result later.

Construction of the multi-reflection tube

On the basis of the above theoretical considerations we shall now describe a practical form of construction of the multi-reflection tube. In the first place there must be a parabolic field or something closely resembling it. As already stated in the foregoing, the parabolic field can be sufficiently approximated for our purpose in a simple way by the combination of an equipotential field and a field with a linearly decreasing potential. Expressed in a different way this means the combination of

1) a space free of field in which the retarded electrons have a longer transit time than the unmodulated electrons, with
2) a linear retarding field in which they have a shorter transit time.

By a suitable choice of the dimensions of the two spaces it is possible to make the two effects compensate each other, so that we actually obtain a practically equal transit time for electrons of divergent velocities, provided these are smaller than the unmodulated velocity.

In *fig. 8* it is shown schematically how the modulator system MM' is surrounded by two grids A and A', which are electrostatically at the same potential as the modulator system. Except for the relatively slight high-frequency A.C. voltage on the electrodes of the modulator system, which causes the retardations and accelerations of the electrons, the two grids A and A' bound an equi-potential space, which we shall call the anode space. Beyond A and A' are the spaces with linearly decreasing potential, respectively towards the cathode K and

the reflection electrode R, which is also at cathode potential. A second point for consideration is how, by simple means, the "waiting time" of $T/2$ of the accelerated electrons is to be attained. Here again the combination of an equipotential space with a field of linearly decreasing potential furnishes a

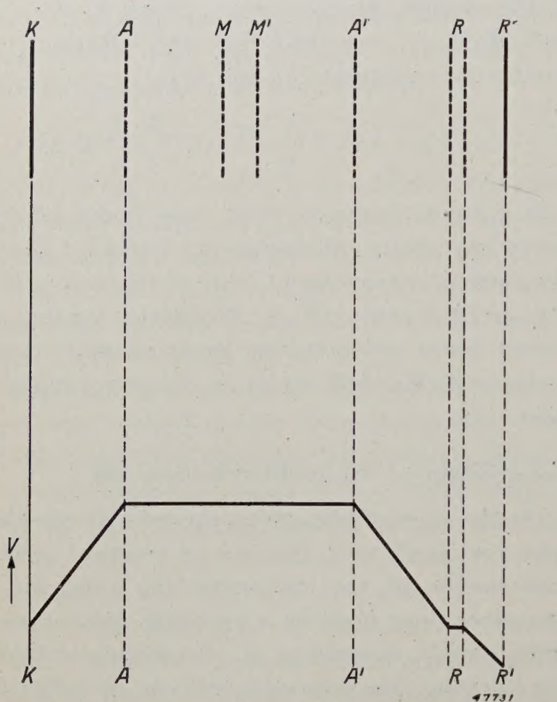


Fig. 8. *a*) Diagram showing the principle of the multi-reflection tube. K cathode; A and A' grids forming the anode; M and M' grids of the modulator system; R' repeller electrode; R grids providing for the desired variation of the potential between the anode and the repeller electrode. *b*) Static potential variation in a multi-reflection tube.

solution. To that end, the electrode R is constructed as a double grid, while behind R there is a second electrode R' to which a variable negative voltage is applied. The short field-free space between the grids of R in combination with the matched linear retarding field between R and R' gives the desired more or less constant waiting time of $T/2$. The electrons that are only slightly accelerated are mainly held up between the grids R, while the strongly accelerated electrons shoot quickly through the double grid but are held up longer in the retarding space RR'. The distances between the electrodes are determined by the choice of the wave length of the oscillations to be excited and of the voltage to be applied between the modulator system and the cathode. The wave length determines the periodic time T of the oscillations, and the voltage, in combination with the distances in question, determines the transit time t_0 of the electrons for one movement to and fro, while the previously derived expression (3)

$$t_0 = (l + {}^1/_2)\, T$$

must be satisfied.

In the diagram of fig. 8 the various electrodes are all represented by grids. The advantage of a grid lies in the practically constant potential over the whole cross-section of the electron beam. A disadvantage, however, is that the grids take up some of the active electrons, and in the case of electrodes with a low potential this is usually accompanied by secondary emission, resulting in electrons with prohibitive velocities getting mixed with the others. Moreover, there is a considerable loss of energy, and the part that is lost is apt to heat the grids to incandescence and cause them to fuse, especially in the case of the electrodes with a high potential. In the practical model the grids are replaced by plates with circular openings. The theory as developed in the foregoing therefore applies actually only for the electrons on the outside of the beam. For the electrons on and near the axis the potential ratios and thus also the transit times are somewhat altered.

We shall not enter into all the mathematical considerations in this paper. Suffice it to say that as far as the axial electrons are concerned the requirement of equal transit times for all retarded electrons and the same transit time $+ {}^1/_2\, T$ for all accelerated electrons is not satisfied. Here the mechanism of overtaking resembles more that of the reflex oscillators with linear retarding field. At the same time it is found that the density distribution of the axial electrons in the returning beam is in phase with the density distribution of the outer electrons, so that the replacing of the grids by plates with circular openings does not, at least, give rise to any fundamental disturbances. It is even not impossible that the action of the axial electrons is of predominating importance in the starting of the high-frequency oscillations in the modulator system, while the outer electrons only become of importance at the higher oscillation voltages and thus determine the efficiency.

Figs. 9a and *b* represent a multi-reflection tube and its components. In *fig. 9c* the construction of the valve is represented diagrammatically. The cathode K is an indirectly heated oxide cathode. In front of the flat emitting side of the cathode is the drilled plate r, which is at a weak negative potential with respect to the cathode and serves to regulate the cathode current. The anode system A, which surrounds the modulator system L, is a rectangular box open at the top and with two circular holes in opposite sides for the passage of the electron beam. The modulator system L con-

sists of two metal strips, likewise provided with holes, forming a quarter-wavelength Lecher system for the high-frequency oscillations to be excited.

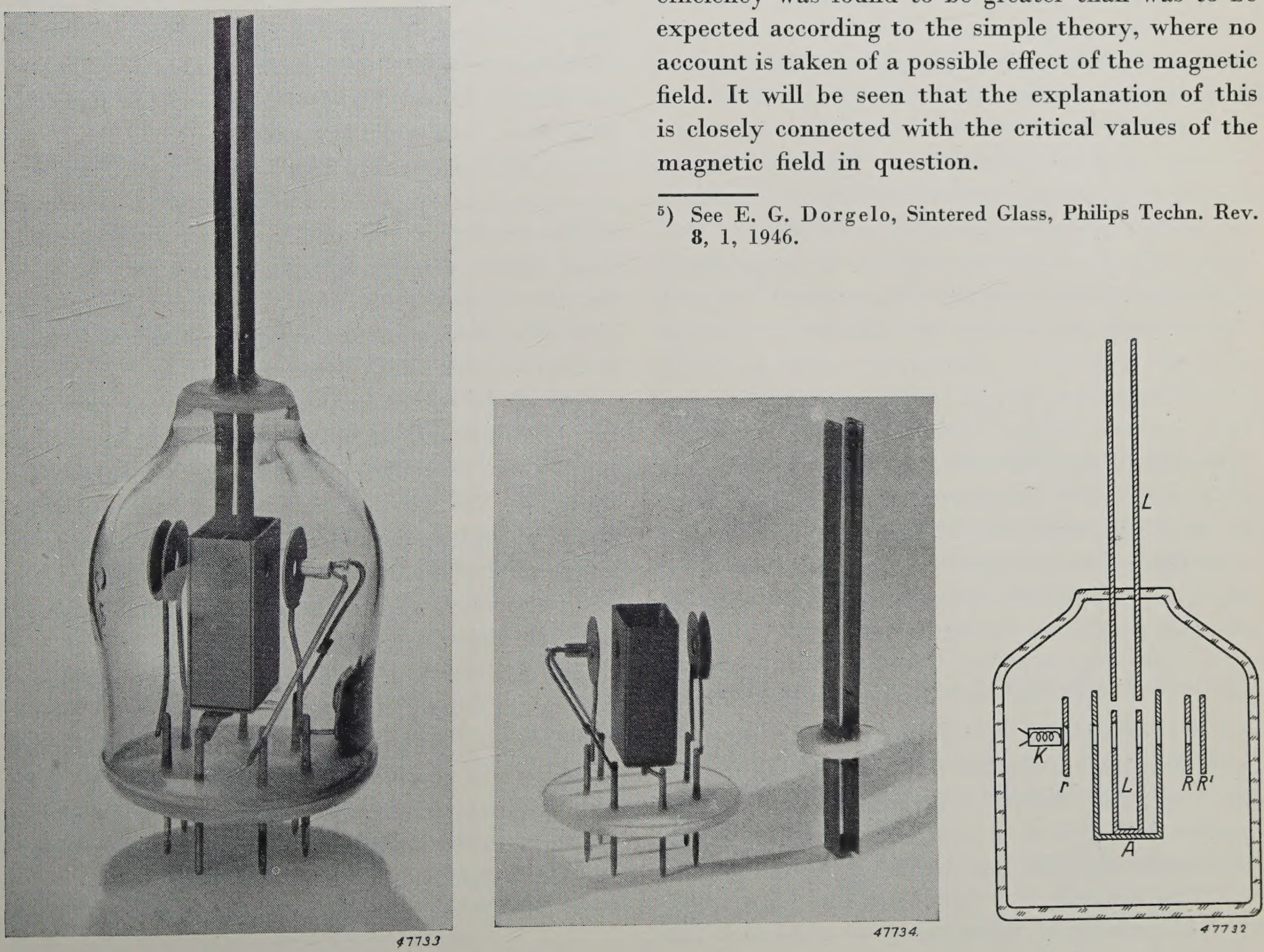
The plates R and R', the first containing an opening, form the reflection system. The plate R is at cathode potential and according to the theory should be constructed as a double grid. The equipotential space enclosed by the double grid, in combination with the retarding field between R and R', has to provide for the constant delay of $T/2$ for all the accelerated electrons. If, however, it is desired to dispense with any form of grid and to deal only with the outer electrons, the plate R will have to be of a certain thickness.

With the arrangement described in the foregoing the Lecher system begins to oscillate with a voltage maximum at the ends of the strips. Opposite these ends there are two other strips of the same width, which take off the high-frequency energy capacitatively and conduct it out of the valve. These strips are passed through the glass with the help of the so-called sintered-glass technique [5]).

Influence of a focussing magnetic field on the efficiency

For a satisfactory functioning of the multireflection tube care must be taken that the electrons are not driven to the electrodes by the lateral forces of the space charge before they have given off the greater part of their high-frequency energy to the modulator system. To that end a magnetic field in the direction of the electron beam is introduced, which opposes the divergence of the beam. At first sight it might be thought that the intensity of this magnetic field could be chosen quite arbitrarily, but that is not so. It is found that the power output of the tube has decidedly certain maxima for certain critical values of the magnetic field. In the discussion of the efficiency we have already stated that with some multi-reflection tubes the efficiency was found to be greater than was to be expected according to the simple theory, where no account is taken of a possible effect of the magnetic field. It will be seen that the explanation of this is closely connected with the critical values of the magnetic field in question.

[5]) See E. G. Dorgelo, Sintered Glass, Philips Techn. Rev. **8**, 1, 1946.



a) b) c)

Fig. 9. *a*) A multi-reflection tube. Diameter of the glass envelope 55 mm. *b*) components *c*) diagram of the multi-reflection tube of *a*); K indirectly heated cathode; r control electrode; A anode; L Lecher system (modulator system); R and R' repeller electrodes.

Let us consider the following experiment:

The Lecher system is detuned, so that the valve cannot oscillate. If the anode voltage is now applied and the current between anode and cathode measured with no magnetic field, we find a certain value. Upon switching on the magnetic field the current falls. This fall is greatest for the above-mentioned critical values of the magnetic field. From a measurement of the magnetic field strength it is found that the critical values are just those at which the cathode is projected electron-optically upon itself, *i.e.* at which the electrons leaving the cathode are brought back to the identical points of the cathode after reflection. The resulting increased space charge in front of the cathode is capable of decreasing the emission of the cathode to a considerable extent, which explains the fact that the fall in the current is a maximum for the critical values of the magnetic field.

What happens now when the tube oscillates at such a critical value of the magnetic field? Owing to their loss of velocity, the originally retarded electrons no longer return to the cathode. After reflection, the originally accelerated electrons lose their excess velocity and consequently return to the cathode, but a closer investigation shows that because of their longer transit time they cannot contribute to the magnetic projection of the cathode on itself. Only the practically unmodulated electrons return to the cathode in a concentrated form and then momentarily suppress the cathode current. This means that the emission is no longer constant, but falls to almost zero twice per cycle. It can be shown that the optimum retarding field then remains the same as for the constant emission. The ratio i_1/i_0, however, becomes greater and consequently also the efficiency. It is not, therefore, so surprising that the efficiency of some multi-reflection valves is found to be higher than 48%, the value found theoretically when disregarding the part played by the magnetic field.

Practical details of the multi-reflection tube

The power that can be yielded by a multi-reflection tube is limited by two factors:
the maximum dissipation permissible for the anode system and the maximum cathode current that the oxide cathode can furnish per cm^2 without detriment to its durability. If 3000 volts is taken for the anode voltage, the area of the cathode can be so chosen that the maximum dissipation for the optimum efficiency is just reached. For the type of multi-reflection tube shown in fig. 9 the effective power is then 15 to 20 watts at a wave-length of 12 cm.

The wave length is fixed for each multi-reflection tube, because of the built-in $\lambda/4$ Lecher system. If, however, it is desired to work with a certain wave-length band it is possible to lead the Lecher system out through the glass wall and to tune it from the outside with a moveable bridge.

The best results are obtained when the transit time t_0 of the retarded electrons for one return movement from and to the modulator system amounts to $3T/2$ or $5T/2$ (this corresponds to $l = 1$ and $l = 2$ in equation (3)). With the same voltages and the same magnetic field a multi-reflection tube can thus work on two wave-lengths, for instance 12 and 20 cm. With a Lecher system that can be tuned oscillations can be set up on these two wave-lengths, and, moreover, the wave-lengths can be varied continuously for a few centimeters above and below; in this case, however, the voltages and the magnetic field must be re-matched each time.

The multi-reflection tube can be used very well as a transmitting valve for all kinds of purposes in the region of very short waves. In particular large types of multi-reflection tubes can be used for the (capacitative) high-frequency heating of all kinds of substances having a strong absorbing power for very short waves.

The multi-reflection tube can be used not only for this ordinary continuous wave operation, but it can be made suitable also for pulsating operation, *i.e.* for the transmission of short wave trains of high intensity. In that case the distances between the electrodes must be adapted to the generally much higher values of the anode voltage used in pulsating operation.

The multi-reflection tube can also be employed as local oscillator in receiving sets working on the superheterodyne principle. Since power plays no great role in receivers, it is of advantage to omit the magnetic field, which of course reduces the efficiency considerably (to about 4-5%) but simplifies the assembly.

LIVING ROOM LIGHTING WITH TUBULAR FLUORESCENT LAMPS

by L. C. KALFF and J. VOOGD.

628.972.6.033

Because of the high efficiency of tubular fluorescent lamps (more than 40 lumen/watt compared with not more than 15 lumen/watt of the incandescent lamp) as well as their good colour-rendering properties, these lamps are suitable in all respects for use in living rooms. The large light flux obtained for a given power consumption makes it possible to realize a more general illumination of the living room, in contrast to the local lighting to which we are accustomed with incandescent lamps. A much larger area of the room can be used for the various activities of the family — reading, writing, mending, etc. At the same time, by placing the tubular lamps against the ceiling and walls instead of in the middle of the room, the whole aspect of the room can be made more spacious. In this article arguments are advanced for the utilization of these possibilities. A series of measurements have been taken in a model room, with a total power input of 150 to 200 W, in which a fixture built into the ceiling and a cornice were used. The merits of different possible light distributions are discussed with reference to isolux diagrams.

Artificial lighting enables us to spend dark evenings more or less according to our own desires. The lighting of homes and especially of the living room has therefore always been of primary importance in practical living as well as in cultural life. It is therefore understandable that eager use has always been made of every new technical possibility for improved interior illumination. The succession of oil lamp and candle, kerosene lamp, gas mantle and electric lamp have marked the most important steps in this development.

Gaseous discharge lamps, which have been developed within the last few decades and among which especially the sodium and mercury-vapour lamps have found many uses because of their high efficiency, were not at first suitable for use in the living room. For that purpose their colour-rendering properties left much to be desired. By the employment of fluorescent substances, however, new possibilities were presented. The result was the familiar tubular fluorescent lamp with an efficiency of about 40 lm/watt and offering a choice in the spectral composition of its radiation by selecting suitable substances for the fluorescent layer [1]). This meant an important advance with respect to colour rendering, even surpassing the modern incandescent lamp; whereas the incandescent lamp must be considered defective in the blue and bluish-green part of the spectrum, with the tubular fluorescent lamp very good colour rendering can be obtained also in those parts.

It is therefore now possible to profit by the above mentioned high efficiency of the tubular fluorescent lamp also for living-room illumination.

In the past developments from oil lamp and candle *via* kerosene lamp and gas mantle to incandescent electric lamps the only thought in each case was to make use of the new invention for "more and easier light", without fundamentally changing the system of illumination. With the introduction of the tubular fluorescent lamp, however, it seems to us that a change in the principles of the lighting system is called for. The jump in efficiency from 15 lm/W for the modern incandescent lamp to 40 lm/W for the tubular fluorescent lamp is so large that an entirely different system of living-room illumination can now be considered. In this article we shall bring forward some conclusions based upon experience and go more deeply into several possibilities.

Localized versus general lighting

When looking around attentively and objectively in all kinds of living rooms one is soon struck by the fact that with the present lighting by means of incandescent lamps much space and freedom of movement is lost. A central lamp with shade hanging at eye level and one or more table or standard lamps form the often voluminous attributes of the usual lighting system, and the result is in most cases a localized lighting which though perhaps more intense is not fundamentally different from that obtained in the times of the candle and the kerosene lamp.

This localized lighting creates a sphere of seclusion which is felt and appreciated by many as an essential element in the peaceful evening hours of home life. On the other hand there are others who regret that the effect of their carefully arranged interiors is to a large extent lost in the evening because of insufficient general illumination, who consider the

[1]) A. A. Kruithof, Tubular luminescent lamps for general lighting purposes, Philips Techn. Rev. **6**, 65, 1941.
Since the word "luminescent" is apt to lead to misunderstanding, it is better to speak of "fluorescent lamps".

fixtures at eye level to be a hindrance to the appreciation of the spaciousness of a room or who regard the system of localized lighting as an undesirable restriction of the utilitarian possibilities of the room. The last point of view will be of especial significance when several members of a family are in the living room at the same time and need for their various occupations a light level of 100 to 200 lux, which with localized illumination is only obtained in a very limited part of the room.

Thus on esthetic as well as on practical grounds the need of a good general illumination of the living room is felt by many. The obvious question, therefore, is why such a general illumination is only very exceptionally found.

In order to obtain some insight into this question we shall begin with the fact that in most countries not more than 150 watts of electric power is used for living-room lighting, a limit which is determined, among other factors, by the ratio of the cost of electrical energy to the standard of living of the population. With these 150 watts when incandescent lamps are used a light flux of at most 2200 lumens is available under the most favourable conditions. Suppose that a living room of ordinary size, for instance 4×5 m², has to be lighted. We shall consider especially the illumination of the "working surface", *i.e.* a surface at table height above the whole floor area of the room. With fixtures placed close above this working surface one can count on a light efficiency of 0.5, so that in the case in question 1100 lumen are available on the working surface. The lighting will be approximately so arranged that an area of at least $2^1/_2$ m² under the central lamp receives an average intensity of 200 lux, while at another spot in the room under a standard lamp about 1 m² receives the same intensity. For the remaining $16^1/_2$ m² of the working surface there is only $1100 - (200 \times 3^1/_2) = 400$ lumen available. The greater part of the room thus has less than 25 lux at table height. The walls are no better off. One may thus rightly speak of "localized lighting".

What light flux, then, would be needed for an efficient system of general illumination?

From considerations of lighting technology, for such a system the fixtures would be placed high, perhaps even against the ceiling. In that way it is easier to obtain a uniform illumination of the working surface and a stronger illumination of the walls. This, it is true, implies that in general the lighting efficiency will be lower; a value of 0.33 can be counted on. The light flux available on the working surface will thus amount to about one-third of the total light flux employed. We shall now assume once more that a level of 200 lux is required on $3^1/_2$ m² of the working surface and that for the remaining $16^1/_2$ m² an average of 80 lux is desired. This, however, still does not leave enough light to allow of work involving eye strain to be done in any arbitrary part of the room. But the usefulness of the room as a whole, compared with the case first described, will be very much improved. With these minimum requirements for a general illumination we arrive at a light flux of about 2000 lumen on the working surface, *i.e.*, according to the above, a total of 6000 lumen.

In addition to the increased usefulness of the room with this illumination, the disappearance of fixtures at eye level and the good illumination of the walls should be noted — advantages which, in the light of the arguments already mentioned, contribute towards making general lighting attractive to many.

To change over from the 2200 lumen for localized lighting to 6000 lumen for general illumination would considerably increase the consumer's light bill if he had only incandescent lamps at his disposal, and this is presumably the reason why the general public has never taken such a step. It is now reasonable to assume that the development of the tubular fluorescent lamp will be able to change this. Because of the much higher efficiency of these lamps the replacement of incandescent lamps for 2200 lumen by fluorescent lamps for 6000 lumen will in the end mean a much smaller increase in the cost. The practical and esthetic advantages of general illumination will then be appreciated more and also the advantage of fluorescent lighting with respect to colour rendering will become indispensable.

These considerations have led us to investigate more closely the practicability of a general lighting system with tubular fluorescent lamps, and here a brief account is given of the results obtained.

Some experiments with tubular fluorescent lamps for general interior lighting.

The name already expresses the fact that the tubular fluorescent lamp is not to be regarded as a point source of light like the incandescent lamp. Therefore the position in which the lamps are to be installed in a room has to be considered from a new angle which was unknown with separate incandescent lamps, namely that of mounting the lamps parallel to lines or planes in the room. For practical purposes this means that these lamps, being straight-lined, are especially suitable for mounting

against walls or ceiling, the very position most suitable for the above-described general illumination. Even when these tubular lamps are placed in fittings, which must be the case in living rooms in spite of their relatively low brightness, this still applies to a certain extent.

The next question is how the lamps required to give the total light flux should be distributed in the room. The 6000 lumen calculated above as the minimum requirement for a general illumination corresponds in the case of fluorescent lamps to a power of about 150 watts, which is just the figure taken above as basis for the present customary lighting with incandescent lamps. Since the fluorescent lamps now available are in units of approximately 40 watts net, three or perhaps four such units can be used to obtain the desired total light flux.

In order to give some idea of the distribution of the light when the necessary lamps are placed in different positions in the room, a number of measurements have been taken with an experimental installation in a test room with a floor area of 5.5×3.5 m^2 and height 2.75 m in which two fittings were installed as shown in *fig. 1.* One is a cornice fitting

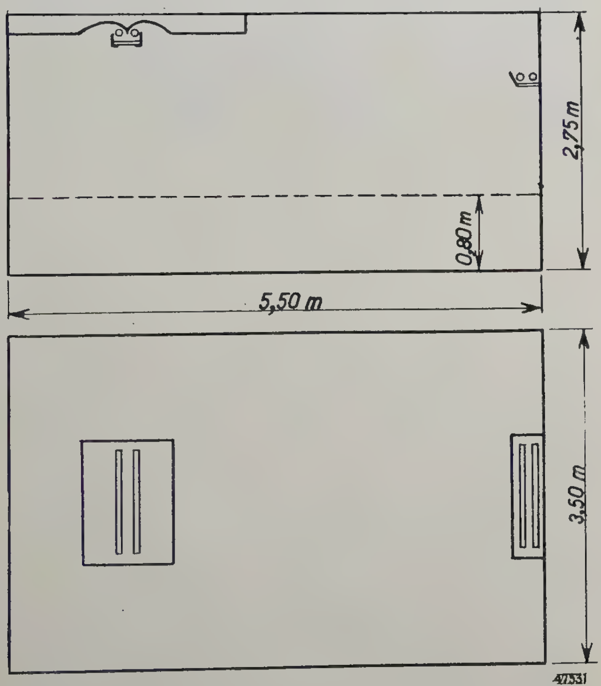


Fig. 1. Plan and elevation of the test room with the two fittings: one let into the ceiling (which was somewhat lower over one half of the room) and one in a cornice on the narrow wall of the room.

placed over a window in one of the shorter walls of the room and shut off from underneath by a plate of frosted glass; this cornice contains two tubular fluorescent lamps of 40 W each. The other fitting is set into the slightly lower ceiling of the other half of the room and consists of two mat-white curved surfaces reflecting into the room the light from two tubular lamps, likewise of 40 W

Fig. 2. Half of the test room with the fitting let into the ceiling.

each; this fitting, too, is shut off underneath by a glass plate which disperses the light. (In actual practice with such a fitting it may be found preferable to replace this horizontal plate by vertical diffusing partitions, so as to avoid loss of light owing to the collection of dust.)

Figs. 2 and *3,* which are photographs of the room with the two fittings, give an impression of the possibilities with such a lighting system as far as the general aspect of the room is concerned.

By switching on a different number of lamps in each fitting, different light distributions were obtained. The horizontal intensity of illumination at table height was measured at a large number of points and the results were plotted in diagrams of isolux lines. (These diagrams apply for lamps yielding exactly 200 Dlm; in practice lamps deviate somewhat from this figure.) In *figs. 4a-d* the floor area of the test room is represented in each case by a series of isolux lines for the cases 2+0, 2+1 and 2+2, respectively, the first number referring to the number of lamps burning in the ceiling fitting and

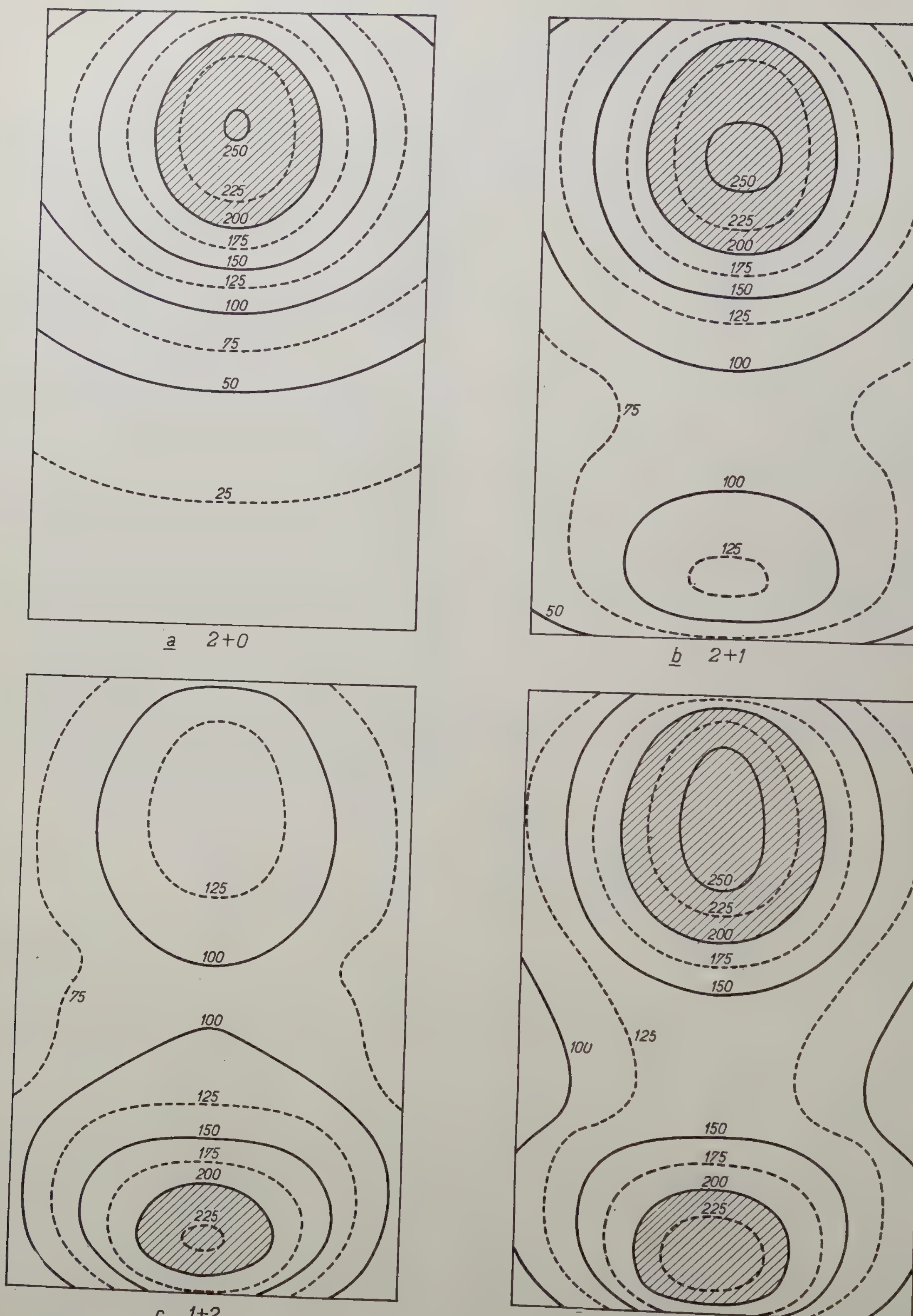


Fig. 4*a-d*. Different distributions of light in the test room obtained with different combinations of the lamps in the ceiling and cornice fittings. Each figure represents a plan of the room with isolux lines of the light distribution on the working surface. The numbers indicate the light intensity in lux. The areas which receive more than 200 lux are cross-hatched. *a*) Refers to the case 2+0 (2 lamps burning in the ceiling fitting, 0 in the cornice), the other figures, as indicated, referring to the cases 2+1, 1+2 and 2+2.

the second to the number burning in the cornice. In the first case (2+0) a large part of the room receives less than 25 lux. The second case (2+1) shows a quite useful distribution with nowhere less than 50 lux, more than 200 lux over an area of 2.5 m^2 and more than 100 lux over 11.3 m^2. In the third case (1+2) the general illumination of the room is still better, being scarcely anywhere below 75 lux, but on the other hand the area with the highest illumination (200 lux) is rather too small, only 0.9 m^2. Finally there is the case 2+2, the isolux diagram of which speaks for itself: there is nowhere less than 100 lux, whilst there are two areas of 3.0 m^2 and 1.1 m^2 with more than 200 lux. It is true that in the last case the total light flux is somewhat greater than was premised, namely 8000 lumen, but it goes to show how with such a relatively small additional power a rather good general illumination (according to our present conceptions) is attained, whereas if incandescent lamps were used this would only be possible by increasing the consumption to two or three times 150 W. Moreover, with the 2+1 illumination (fig. 4b), where the power consumption budget is certainly not exceeded, the result is satisfactory in most respects.

Fig. 3. Other half of the test room with cornice fitting over the window.

In conclusion we may say that, thanks to the high efficiency of the tubular fluorescent lamps, our present day lighting system for the living room can not only be improved but actually revised. Especially for the smaller homes, where more intensive use is made of the living room, the system here described, with its high level of general illumination and inconspicuous fittings, is most appealing. Lamp manufacturers, lighting architects and occupants will have to cooperate if the possibilities indicated here are to be brought to full development.

A VOLTAGE STABILIZING TUBE FOR VERY CONSTANT VOLTAGE

by T. JURRIAANSE.

621.316.722.1: 621.384.5

Glow-discharge tubes can be so constructed that the working voltage is independent of the current within a fairly wide region of currents. Such tubes may therefore be used for the stabilization of voltages. However, even the best stabilizer tubes at present available have two drawbacks. In the first place they are not stable, the working voltage, *i.e.* the stabilization voltage, varying considerably for different specimens of the same type of tube, giving variations of 10 to 15 volts at a nominal voltage of, for instance, 100 volts. In the second place the working voltage varies with time: a variation of 10 to 15 volts during the life of the tube is quite common. Stabilizing tubes have now been developed by Philips which are practically free of these drawbacks, the variation of the working voltage for different specimens varying by not more than a few volts, while the variation with time is not more than $^1/_2$ volt per 1000 working hours. This great improvement has been attained by using a carefully prepared molybdenum cathode and depositing a thick layer of molybdenum on the walls of the tube by sputtering the cathode in a gas discharge. With the new stabilising tube ambient temperature has but little effect on the voltage. This temperature effect, which was completely overshadowed by the above-mentioned large voltage variations in other stabilising tubes, is discussed at the end of the article.

Introduction

In an electrical apparatus it is often necessary that the D.C. voltage should be independent of variations in the supply voltage. The grid voltage of an amplifier valve, for example, should be very constant, since any fluctuations may cause a variation of the amplification. It may also be desired to smooth the voltage ripple which is retained after rectification of A.C. voltage.

This stabilization of voltage can be achieved in a simple way by means of gas-discharge tubes [1]). The glow discharge is particularly well adapted for such purposes, as will appear from the following.

A glow discharge occurs between two electrodes in an atmosphere, for instance, of a rare gas at pressures of 0.5 to 40 mm of mercury when the cathode is cold and thus gives no thermionic emission of electrons. At voltages of 100 to 200 volts a luminous aura is seen around the cathode — the glow — which is separated from the cathode by a dark layer, Crookes dark space. If the current through the tube is small the surface of the cathode is not completely covered by the glow, the latter appearing as a sharply defined spot on the anode. When the current is increased the spot spreads, while both the current density, which is of the order of 1 mA/cm², and the voltage on the tube remain constant, until the glow has completely covered the surface of the cathode.

In this current region the so-called normal glow discharge takes place (*cf. fig. 1*). Once the whole cathode is covered by the glow, a further increase in current necessarily increases the glow-current density and the voltage over the tube also increases. This is then the region of the anomalous glow discharge.

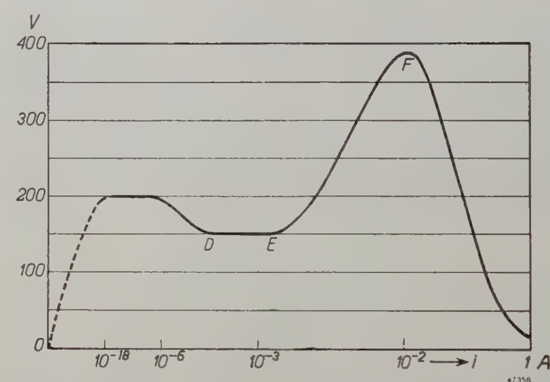


Fig. 1. The voltage V on a gas-discharge tube as a function of the current i (represented diagrammatically). Several values of the current are indicated, although not to scale, in order to show the order of magnitude of the current at which a given type of discharge occurs. To the left of E is the region in which breakdown occurs. The region between E and D corresponds to the "normal glow discharge". To the right of D the glow discharge is anomalous. To the right of F is the region of arc discharge.

In the region of the normal glow discharge, therefore, the voltage on the glow discharge tube is independent of the current. Upon this fact is based the possibility of using a glow-discharge tube for stabilization of voltage.

The change of potential between the electrodes of the tube is not linear. In *fig. 2* it may be seen that the voltage drop takes place mainly near the cathode; this is called the cathode drop. The distance covered by this potential difference corresponds quite well to the depth of the Crookes

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[1]) Another method of stabilization is described in Philips Techn. Rev. 4, 54, 1941.

dark space. There is sometimes also a voltage drop close to the anode, which is called the anode drop and which is visible on the anode as a luminous film or globule. This voltage drop amounts to 10 to 20 volts, much less than the cathode drop, which

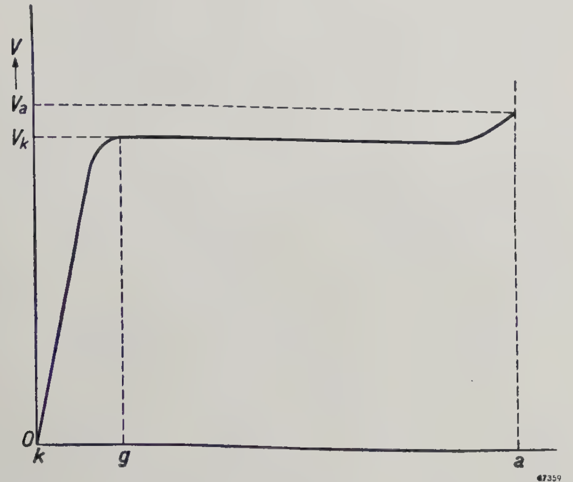


Fig. 2. The voltage distribution between the cathode and the anode of a glow discharge tube. V_k is the cathode drop; V_a is the voltage of the anode with respect to the cathode, *i.e.* the working voltage; V_k—V_a is the anode drop. At *k*, *a* and *g*, respectively, are the cathode, the anode and the boundary between the Crookes dark space and the glow.

is 100 to 200 volts. Between these two regions of drop in potential the voltage is fairly constant. In the following we shall speak only of tubes with no anode drop, unless the contrary is especially stated, so that the working voltage measured is equal to the cathode drop. Thus for the tubes in question the cathode drop is equal to the working voltage. When the tube burns in the region of the normal glow discharge the cathode drop is also called normal.

The value V_n of the normal cathode drop is determined by the material of the cathode and the nature of the gas. *Table I* gives a survey of several

Table I,

The normal cathode drop V_n (in volts) for different combinations of gases and cathode materials

	neon	argon	nitrogen
barium	—	95	155
graphite	200	—	—
iron	150	165	215
potassium	70	65	170
molybdenum	115	—	—
nickel	140	130	195

values of that voltage as given in the literature for different combinations of gases and cathode materials.

The glow-discharge tube as voltage-stabilizing tube

For purposes of stabilization the discharge tube is connected with the voltage source *via* a series resistance (see *fig. 3*). The load *B*, which is here shown as a resistance, is connected across the glow-discharge tube. The essential point is that a voltage variation of the source shall be taken up completely in the series resistance, since the variation of the current through the tube causes no change in the working voltage.

The load thus experiences no fluctuations in voltage.

The series resistance and the load will usually be so chosen that at the average value of the voltage from the source the glow-discharge tube carries a current at which the glow half covers the cathode, so that the variations of the current through the tube in both directions can be a maximum.

Now in practice the cathode surface will not be uniform physically. Very slight contaminations of the surface have a large influence on V_n, so that the values of table I give only a rough impression. A variation of 30 volts in the values given in the literature is no exception. The contaminations mentioned result in different parts of the cathode having different normal cathode drops. In that case current variations do indeed cause voltage changes. The

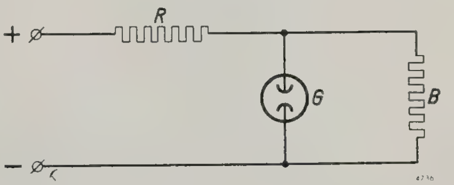


Fig. 3. The circuit diagram of a voltage stabilizing tube. *G* glow-discharge tube, *R* series resistance, *B* load.

differential resistance dV/di, also called internal resistance R_i of the tube, will then differ from zero, since the glow discharge will first pick out those parts of the cathode where V_n is lowest. Now the quality of the tube is higher the lower the internal resistance. It is thus clear that some care must be taken in preparing the surface of the anode.

The position of electrodes with respect to the wall and to each other can also affect V_n and thus also R_i. In particular V_n and R_i will increase when the glass wall is in the immediate vicinity of the glow-discharge, due to the fact that the positive and negative carriers or charge can reunite on the wall.

For many purposes satisfactory values of R_i

have been successfully obtained and a number of tube types for various current ranges and voltages have been manufactured by Philips for many years. The different voltages are obtained by using different combinations of gases and cathode materials (table I). Some types for 100 volts have an iron cathode covered with barium, in combination with a mixture of rare gases, usually containing neon with several tenths of a percent of argon. By the addition of this small quantity of argon the fairly high breakdown voltage of neon is reduced to a practical value approximating to the working voltage. Other tubes for 100 volts have an iron cathode covered with magnesium and a gas filling of a different neon-argon mixture.

A very low internal resistance is obtained in the case of the type 100 *E1* by not only preparing the cathode with great care, but also by choosing the most favourable geometrical arrangement of the electrodes. The tube has three concentric cylinders with several millimeters intermediate space, in which the discharge takes place. The inner and outer cylinders are the anode, the middle one the cathode, so that both sides of the surface can be covered by the glow-discharge up to a maximum current of 200 mA. The glow-discharge, no matter what its extent, thus always burns under geometrically almost equivalent conditions, while the above-mentioned recombination of the ions on the walls is out of the question.

The voltage stabilizing tube for very constant voltage

From the above it is clear that it has long been possible to construct glow-discharge tubes with low internal resistance. For many applications, however, there is the drawback that the working voltages of different tubes of the same type vary so much, and, moreover, that in the course of time the working voltage of a given tube may vary considerably. The figures given for the voltage tolerance of the usual stabilisation tubes are sufficiently proof of this. The deviations in the values of the working voltage and the variation during the lifetime are usually of the same order of magnitude and may amount from 10 to 15 volts.

We have now, however, succeeded in developing a tube which, in addition to the normal good smoothing with a low differential resistance, also has a working voltage which does not vary more than 0.5 volt in 1000 hours and the tolerance of which does not exceed 2 to 3 volts as between the different experimental specimens. From the following it will be seen that the essential factors responsible for this are the use of molybdenum as cathode material, the cleaning of the cathode surface by sputtering in the glow discharge and finally the deposition of a layer of atomized cathode material on the walls of the tube; this atomization is accomplished by continuing the sputtering for a long time after the cleaning of the cathode.

The phenomena observed when a glow discharge, for instance in pure neon at a pressure of 20 mm of mercury, is allowed to burn on a chemically well cleaned molybdenum surface are as follows [2]).

When the current is so large that the glow-discharge entirely covers the cathode, after burning for five or ten minutes the cathode glow will be seen to contract to a small part of the cathode surface, the working voltage meanwhile falling from about 300 to 150 volts. The glow-current density rises from about 0.5 mA/cm^2, corresponding approximately to the normal current density, to one hundred times that value. If the current through the tube is now increased slightly the intensity of the light in the cathode spot increases, while the glow at the same time begins slowly to spread out, the glow discharge, however, remaining entirely anomalous.

This continues until the whole cathode is again covered by the glow. If after some time the current through the tube is diminished until the discharge is normal, the low normal current density of about 0.5 mA/cm^2 is recovered, which initially prevailed at the high voltage of 200 volts but is now found at about 108 volts.

If the glow is now allowed to continue to burn at this low current, after several minutes the working voltage is observed to rise, at first only little, but ultimately by several tenths of a volt. This rise in the working voltage can also be brought about for instance by adding to the neon several hundredths of a percent of oxygen after the low working voltage has been reached. The conclusion is that the low working voltage corresponds to a molybdenum surface which has been cleaned by sputtering in the discharge with high current density, and that during the burning with a low current density the contaminations which have been liberated spoil the clean surface again.

This latter effect can now be avoided by continuing the sputtering after the cleaning of the cathode surface, until a good thick layer of atomized molybdenum is deposited on the walls of the tube. It therefore seemed obvious to assume that the

[2]) *Cf.* F. M. Penning and J. H. A. Moubis, Philips Res. Rep. 1, 119, 1946.

contaminations in question came out of the glass walls, and this was confirmed by further investigation. The sputtered molybdenum can act as a getter to take up these small quantities of gas.

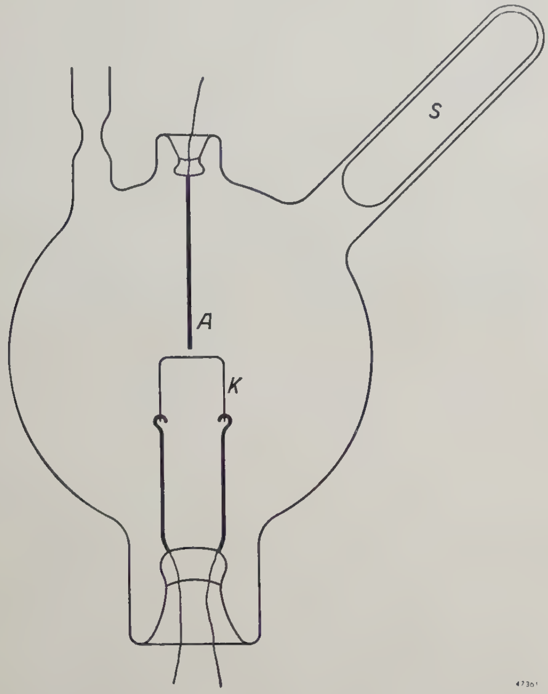


Fig. 4. Arrangement for demonstrating the liberation of contaminations from the wall by the glow discharge. *A* anode, *K* cathode, *S* moveable glass rod.

In addition, however, it is found that the discharge itself frees gases from the glass walls, so that the sputtered layer serves as a shield between the discharge and the glass wall. Only after the deposition of this layer could a voltage variation of less than 0.5 volt, often only 0.1 volt, per 1000 hours be obtained.

The following simple experiment clearly demonstrates that the discharge does actually free the contaminations from the glass. In a side tube of a discharge tube with a molybdenum cathode (*cf. fig. 4*) a glass rod *S* is placed in such a way that by shaking the tube it can be moved toward or away from the cathode. When the tube is evacuated and the cathode sputtered the rod lies at the back of the side tube, so that no sputtered molybdenum reaches it. When the cathode has been sputtered long enough for so much molybdenum to be deposited on the glass walls that the working voltage, reckoned over many days, remains constant, then upon the glass rod being brought within a distance of say 1 cm of the cathode, the working voltage will rise at a rate of about 5 mV per minute.

After some time the cathode even becomes so contaminated that the cathode spot begins to contract. When the rod is again shaken into the back of the side tube the variation of the working voltage ceases immediately and even reverses its direction, due to the fact that the cathode is restored under the influence of the glow-discharge. The gaseous contaminations are removed from the cathode and taken up in the sputtered layer of molybdenum on the walls. This porous layer of metal thus acts not only as a getter [3]) but also as a shield between the discharge and the walls.

Due to the measures described, the value of the normal cathode drop is now very satisfactorily reproducible and varies only a few volts for different tubes. In pure neon at a pressure of 40 mm the average value of V_n is about 106.5 volts; in 10 mm argon about 103.5 volts and in neon with $^1/_2$ percent argon 84.5 volts. *Fig. 5* shows a practical model of the tube for 8 mA and 85 volts stabilization voltage.

Many other metals can also be treated in this way and give reasonably reproducible values of V_n, but molybdenum and zirconium give the best results

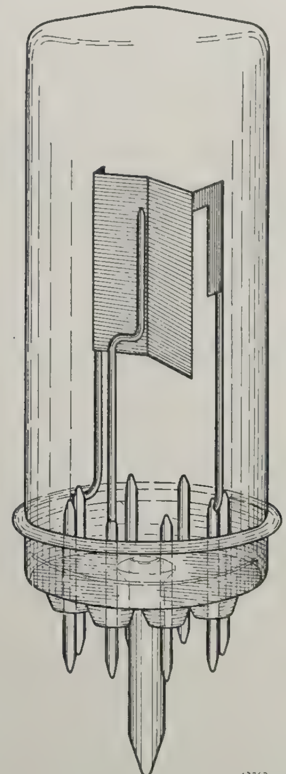


Fig. 5. Practical model of the new stabilizing tube for very constant voltage. The rod-shaped electrode is the anode, the plate is the molybdenum cathode. Actually the interior of the tube is scarcely visible through the black layer of sputtered molybdenum of the walls.

[3]) *Cf.* T. Jurriaanse, F. M. Penning and J. H. A. Moubis, Philips Res. Rep. 1, 225, 1946.

and also offer the advantage in manufacture that, notwithstanding the high current density during the sputtering, the glow discharge contracts entirely on to these cathode materials. The current leads on which the molybdenum or zirconium are mounted are usually made of materials which have a much higher normal cathode drop (for nickel, for instance, $V_n \approx 140$ volts).

The temperature coefficient of voltage stabilizating tubes

Now that it is possible to make tubes with a voltage which is independent of the current and time, another variation of the working voltage becomes of importance, to which previously no attention had been paid. This is the variation of the working voltage according to the ambient temperature. With the various older types of stabilizing tubes this variation amounts to 20 to 30 mV per degree centrigrade, the value being a negative one in the tubes which have no anode drop. The new tube with molybdenum cathode for 8 mA and 85 V has a still smaller temperature coefficient, lying below —10 mV per degree. This slight dependence on temperature cannot be entirely avoided, as will appear from the following.

According to the generally accepted view, the value of the normal cathode drop is independent of the density of the gas, so that no effect from the ambient temperature should be expected. The actual situation, however, does not appear to be so simple.

In the first place, from measurements which were made possible by the fact that the value of V_n is very well reproducible when the cathodes are prepared according to the above-described method of procedure, it appeared that the normal cathode drop V_n is indeed dependent on the gas density, as *fig. 6* shows for the gases neon and argon.

In the second place, the gas density varies somewhat in the vicinity of the cathode when the temperature of the surroundings of the tube changes. The glow heats the cathode with a power approximately equal to the voltage consumed by the tube, since the whole voltage drop is taken up in a gas layer several tenths of a millimeter thick around the cathode. The cathode is thus at a higher temperature than the walls of the tube, so that the density of the gas at the cathode is less than at the walls. Approximately the densities referred to are inversely proportional to the absolute temperatures at those points.

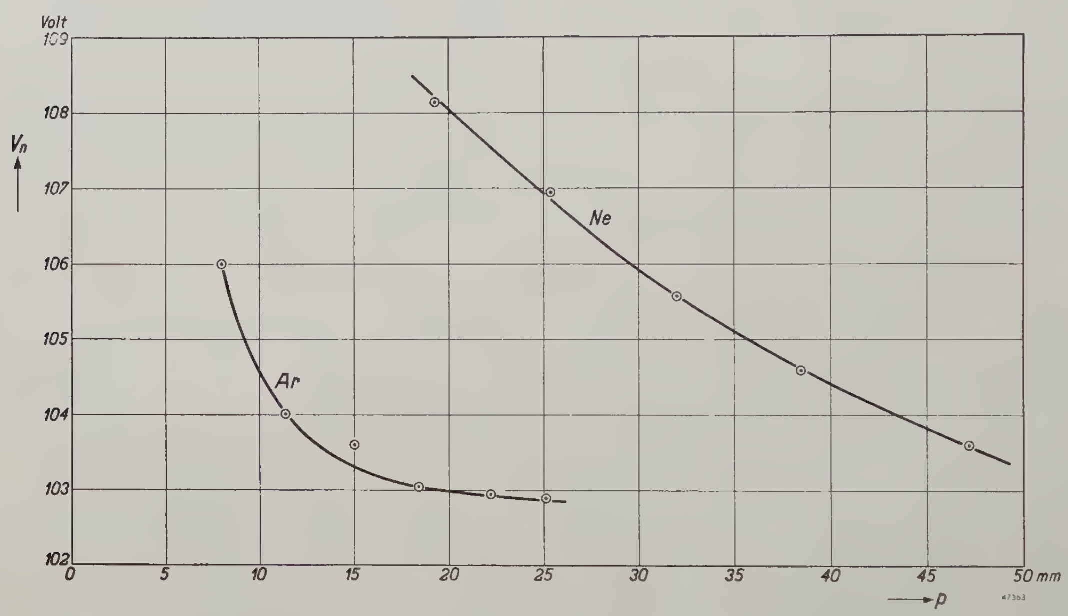


Fig. 6. The normal cathode drop V_n as a function of the gas pressure p for argon (Ar) and neon (Ne).

Now if at a given current through the tube, and thus with a given power consumed, the ambient temperature T_1 is increased by t degrees, in the first instance the temperature T_2 of the cathode will also rise by t degrees, at least if the coefficient of heat conductivity is independent of the temperature. Now, however,

$$\frac{T_2+t}{T_1+t} < \frac{T_2}{T_1},$$

in other words the ratio of the temperatures and thus

that of the densities more nearly approaches unity. Thus if the ambient temperature becomes higher the density near the cathode rises, and according to fig. 6 the cathode drop decreases. It is clear that a negative temperature coefficient of the working voltage is the result, as was indeed found experimentally. Actually, however, the coefficient of heat conductivity of the gas is by no means independent of the temperature, and, moreover, the transfer of heat by radiation also plays an important part.

Due to these causes, as T_1 increases so the quotient T_2/T_1 approaches unity even more closely than was the case before [4]).

The coefficient of heat conductivity is about proportional to $\sqrt{T}$, so that for the same transfer of heat at a higher temperature a smaller temperature gradient is required than at a lower temperature. And, finally, the difference in radiation between cathode and wall of the tube, which is necessary for a given transfer of heat and is approximately proportional to T_2^4-T_1^4, is reached with a smaller temperature difference according as T_1 is higher.

For certain applications which have become possible due to the new construction of stabilizing tube the unavoidable temperature effect here described will therefore have to be taken into account.

[4]) Dr. T. Jurriaanse, Philips Res. Rep., to appear shortly.

IMPEDANCE MEASUREMENTS WITH A NON-TUNED LECHER SYSTEM

by J. M. van HOFWEEGEN.

621.317.33.029.63

A method is described by which impedances can be measured whose resistance component is of such a magnitude that measurement by a previously described method is practically impossible. The characteristic feature of this method is the use of a Lecher system which is not tuned to the measuring frequency. By measuring the variation of voltage occurring along the Lecher system when it is loaded by the impedance to be measured, the so-called reflection factor can be determined. From this reflection factor the unknown impedance can be calculated, whereby a diagram can be used to advantage. The instrument used for measuring the voltage must be calibrated only relatively, just as in the measurements with a tuned Lecher system. A method of measurement is finally described in which the measuring instrument need not be calibrated at all.

In a previous article [1]) a method was described by which impedances can be measured at wave lengths shorter than 1 metre. There use is made of a Lecher system tuned to the measuring frequency. Attention was drawn to the fact that with the use of a short-circuited Lecher system of a quarter wave length this method is only suitable for measuring impedances the resistance component of which is at least several times larger than the characteristic resistance ζ. By using a short-circuited Lecher system of a half wave length impedances can be measured of which the resistance component is at least several times smaller than the characteristic resistance. Impedances having a resistance component of the same order of magnitude as the characteristic resistance (*i.e.* from 10 ζ to $\zeta/10$) cannot, therefore, be measured by the method described. Since the wave resistance of practically usable Lecher systems always lies within rather narrow limits (100 to 300 ohms), there is a rather large region of resistance, from about 30 to about 1000 ohms, which cannot be practically measured by the method in the article mentioned. It is, however, still possible to measure resistances of this order of magnitude with the help of a Lecher system but a different principle has to be applied. The characteristic feature of the method is that use is made of a Lecher system which is not tuned to the measuring frequency. By measuring the variation in voltage which occurs along such a Lecher system when the system is terminated by the impedance to be measured, the so-called reflection factor can be determined, from which the unknown impedance can be calculated. In the following we shall describe the way in which this principle is worked out.

Principle

In order to explain the method of measurement followed here, we will first deal briefly with the mathematical considerations. We begin with the familiar differential equations for voltage and current in the two conductors of a Lecher system [2]).

When a sinusoidal A.C. voltage E with the angular frequency ω (*fig. 1*) is applied to one of the extremities of a Lecher system we may write for the complex representations of voltage and current at an arbitrary point on the Lecher system $Ve^{j\omega t}$ and $Ie^{j\omega t}$, where V and I are complex quantities depending exclusively on the point on the Lecher system, and thus not on the time. The following differential equations now hold for V and I: [3])

$$\left.\begin{aligned}\frac{\mathrm{d}V}{\mathrm{d}y} &= I\,(r^I + j\omega L^I)\\ \frac{\mathrm{d}I}{\mathrm{d}y} &= V\,(g^I + j\omega C^I)\end{aligned}\right\} \quad . \; . \; . \quad (1)$$

In these equations y is the distance from the point in question on the Lecher system to a certain point chosen as zero point (here the right-hand end,

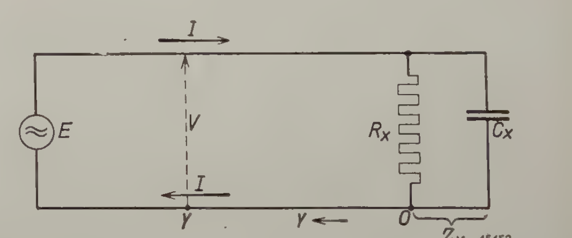


Fig. 1. Lecher system terminated at one end by a connection in parallel of a resistance R_x and a capacity C_x and at the other end connected with a source of high-frequency voltage E. At a distance y from the right hand end the voltage and current are, respectively, V and I.

see fig. 1); r^I en L^I are respectively the resistance and the self-induction per unit of length of the two

1) Philips Techn. Rev. **8**, 1946.

2) *Cf.* also: Philips Techn. Rev. **6**, 240, 1941.

3) These equations are not given in the more usual form, in which one of the members has the opposite sign, because here the coordinate y is reckoned from the end to which the source of voltage is *not* connected (see fig. 1).

conductors together, while g^I and C^I represent respectively the shunt conductance and the capacity between the two conductors, also per unit of length. The following equations for V and I can be derived from (1) in a simple way:

$$\left.\begin{aligned}\frac{d^2V}{dy^2} &= \gamma^2 V\\ \frac{d^2I}{dy^2} &= \gamma^2 I\end{aligned}\right\} \quad . \; . \; . \; . \; . \; . \; . \quad (2)$$

γ being here the so-called **propagation constant**, which is given by the formula:

$$\gamma = \sqrt{(r^I + j\omega L^I)\,(g^I + j\omega C^I)} \quad . \; . \quad (3)$$

The solution of the first of equations (2) is as follows:

$$V = Ae^{+\gamma y} + Be^{-\gamma y}\,, \quad . \; . \; . \; . \; . \; . \; . \quad (4)$$

where e is the base of natural logarithms and A and B are integration constants, which therefore do not depend upon the position but are determined by current and voltage at one spot on the Lecher system. From (4) and the first of equations (1) it now follows for I that

$$I = \frac{A}{\zeta}\,e^{+\gamma y} - \frac{B}{\zeta}\,e^{-\gamma y} \quad . \; . \; . \; . \; . \quad (5)$$

In this equation ζ is the so-called **surge impedance** or **characteristic impedance**, for which the following formula holds:

$$\zeta = \sqrt{\frac{r^I + j\omega L^I}{g^I + j\omega C^I}} \quad . \; . \; . \; . \; . \; . \quad (6)$$

In general γ and ζ are complex quantities.

We now set

$$\gamma = \alpha + j\beta \, . \; . \; . \; . \; . \; . \; . \; . \quad (7)$$

If we first disregard the losses of the Lecher system ($r^I = 0$, $g^I = 0$), then according to (3) $\gamma = j\omega\sqrt{L^I C^I}$ and is thus purely imaginary, so that according to (7) $\alpha = 0$, $\beta = \omega\sqrt{LC}$.

The wave impedance is now real and ζ is equal to $\sqrt{L^I/C^I}$. One now speaks of the **surge resistance**. For equations (4) and (5) may now be written:

$$\left.\begin{aligned}V &= A\,e^{+j\beta y} + B\,e^{-j\beta y}\\ I &= \frac{A}{\zeta}\,e^{+j\beta y} - \frac{B}{\zeta}\,e^{-j\beta y}\end{aligned}\right\} \quad . \; . \; . \; . \quad (8)$$

If, as is represented in fig. 1, the right-hand end is terminated by an impedance Z_x, for $y = 0$ the ratio of V to I is equal to Z_x, and thus

$$Z_x = \frac{A+B}{A-B}\,\zeta, \quad . \; . \; . \; . \; . \; . \; . \quad (9)$$

from which it follows that

$$B = A\,\frac{Z_x - \zeta}{Z_x + \zeta} \quad . \; . \; . \; . \; . \quad (10)$$

so that for the first of equations (8) we may write

$$V = A\left\{e^{+j\beta y} + \frac{Z_x - \zeta}{Z_x + \zeta}\,e^{-j\beta y}\right\} \quad . \; . \; . \quad (11)$$

The quantity

$$f = \frac{Z_x - \zeta}{Z_x + \zeta}, \qquad (11a)$$

which is in general complex, is usually termed the **reflection factor**. We shall explain its significance in the following.

For the complex representation of the voltage we may now write:

$$Ve^{j\omega t} = A\left\{e^{j(\omega t+\beta y)} + fe^{j(\omega t-\beta y)}\right\} \quad . \; . \quad (12)$$

We now represent the argument of the complex quantity f by φ and the modulus by $|f|$, so that $f = |f|e^{j\varphi}$.

As is known, the momentary value of the voltage is equal to the real part of its complex form. From (12) it now follows for this momentary value that

$$V_{mom} = A\left\{\cos(\omega t + \beta y) + |f|\cos(\omega t - \beta y + \varphi)\right\} \quad (13)$$

The first term of the binomial between the brackets represents a wave travelling towards the **right**, while the second term represents one travelling towards the **left**. These two waves are usually called the incident (or direct) and the reflected (voltage) waves. The wave length of the two waves is determined by the equation

$$\beta\lambda = 2\pi \, . \; . \; . \; . \; . \; . \; . \; . \; . \quad (14)$$

The complex representation of incident and reflected waves, is, according to (12), given by $Ae^{j(\omega t+\beta y)}$ and $Afe^{j(\omega t-\beta y)}$, respectively. For $y = 0$, *i.e.* for the reflecting end where Z_x is connected, these expressions become

$$Ae^{j\omega t} \text{ and } Afe^{j\omega t}, \text{ respectively.}$$

This shows us the significance of f: it is the ratio of the complex representations of reflected and incident waves at the reflecting end.

We shall now consider the incident and reflected waves in more detail for three simple cases (*cf.* expression (11*a*) for f).

a) When the impedance Z_x is equal to ζ, f becomes equal to zero, *i.e.* there is no reflected wave. The incident wave which is then present alone is called a **pure travelling wave**.

b) If the reflecting end is open $f = 1$, *i.e.* at that

end the incident and the reflected voltage waves are equal in intensity and phase.

c) If the reflected end is short-circuited $f = -1$, *i.e.* at that end the incident and the reflected voltage waves are equal in intensity and opposite in phase.

In cases b) and c), due to the superposition of the two waves, at certain spots lying at intervals of a quarter wave length alternate voltage minima and maxima (nodes and antinodes) occur. We then speak of standing waves. The equation for this is found by calculating the effective value of the A.C. voltage given by (13). After some reduction we find

$$V_{eff} = \frac{1}{\sqrt{2}} A \sqrt{1+|f|^2 + 2|f| \cos(2\beta y - \varphi)} \quad . \quad (15)$$

A voltage minimum occurs for those values of y for which $\cos(2\beta y - \varphi) = -1$ and at that minimum according to (15) the voltage is

$$V_{eff\ min} = \frac{1}{\sqrt{2}} A \,(1 - |f|) \quad . \; . \; . \; . \; . \; . \quad (16)$$

In the above-mentioned cases b) and c) where $|f| = 1$, therefore the voltage at the minima is always zero. We might then speak of pure stationary waves. Such waves also occur when a loss-free Lecher system is terminated by a loss-free reactance. In that case Z_x is of course purely imaginary. From (11a) it then follows, since ζ is real, that $|f| = 1$. If, however, the load impedance Z_x contains a resistance component, $|f| \neq 1$ and thus the voltage is not zero at the minima.

The theory given in the foregoing holds for every form of transmission connection and thus not only for a Lecher system, which is actually nothing but a short section of transmission line used at a very high frequency.

Determination of the reflection factor

According to (15) the positions of the voltage maxima and minima, as well as the further curve of the voltage as a function of y, depend upon $|f|$ and φ, thus on the impedance connected at the end. By measuring this voltage along the Lecher system we can determine $|f|$ and φ, and from them Z_x. The measurement of the variation in voltage can be carried out by means of a measuring instrument (diode voltmeter) which can be slid along the two conductors (*fig. 2a*). We then find a variation in the voltage like that reproduced for instance in fig. 2*b*.

The argument φ of f can be determined from the distance from the end of the Lecher system to the first voltage minimum. The formula for that is

$$\varphi = \frac{4\pi y_0}{\lambda} - \pi \quad . \; . \; . \; . \; . \quad (17)$$

where y_0 is the distance mentioned (see fig. 2*b*).

The modulus of f can be determined in two different ways. In the first method the variation of the high-frequency voltage is measured in the neighbourhood of a minimum. We then measure to

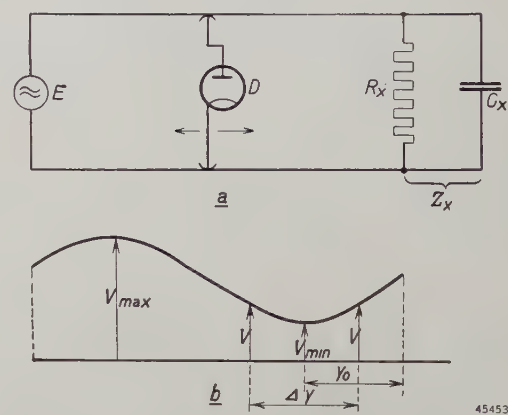


Fig. 2*a*) Diagram showing the principle of the method by which impedances can be measured with the help of a non-tuned Lecher system. Source of voltage E, impedance to be measured Z_x. The shape of the high-frequency voltage curve along the Lecher system is measured with the sliding diode D.
b) Curve of the high-frequency voltage V along the Lecher system.

either side of the minimum the distance at which the voltage is a certain number of times larger than the voltage at the minimum. When V is the voltage at two points which are symmetrical with respect to a minimum and lie at a distance Δy from each other (see fig. 2*b*), the relation between V and $V_{\min}$ is determined by:

$$\frac{V}{V_{min}} = \frac{\sqrt{1 + |f|^2 - 2|f| \cos\left(2\pi \frac{\Delta y}{\lambda}\right)}}{1 - |f|} \quad . \; . \quad (18)$$

Thus if Δy is measured for a certain value of $V/V_{\min}$, for instance for $V/V_{\min} = \sqrt{2}$, $|f|$ can be calculated according to (18).

If Δy is small compared with λ, formula (18) can be further simplified by expanding $\cos(2\pi\Delta y/\lambda)$ into a series. For $V/V_{\min} = \sqrt{2}$ we then have

$$2\pi \frac{\Delta y}{\lambda} = \frac{1 - |f|}{\sqrt{|f|}} \quad . \; . \; . \; . \; . \; . \; . \quad (19)$$

In the second method of determining the modulus of f the ratio between the voltage at a maximum, $V_{\max}$, and the voltage at a minimum $V_{\min}$, is measured. Since the distance between two voltage maxima is equal to a half wave length, in formula

(18) Δy is then equal to $1/2\lambda$, so that the formula becomes

$$\frac{V_{max}}{V_{min}} = \frac{1 + |f|}{1 - |f|} \quad . \quad . \quad . \quad . \quad . \quad (20)$$

In the discussion of the causes of errors of measurement we shall also discuss the question of the advantages and disadvantages of these two methods of determining the modulus of f.

Losses of the Lecher system

In the foregoing it was assumed that the Lecher system was free of loss ($\alpha = 0$). If we had not made that assumption the equation for the variation of the voltage along the Lecher system would have been the following:

$$V_{eff} = \frac{1}{\sqrt{2}} A \sqrt{e^{2\alpha y} + |f|^2 e^{-2\alpha y} + 2|f| \cos(2\beta y - \varphi)}. \quad (21)$$

Now it is easy to understand that for a normal Lecher system $e^{2\alpha y}$ will deviate very little from unity. Due to the loss-free dielectric (air) $g^I = 0$, while owing to the very high frequency ωL^I is very large compared with r^I. From (3) and (7) it now follows that $\alpha \ll \beta$, or, in connection with (14): $\alpha\lambda \ll 2\pi$. Since a Lecher system constructed for the measurements in question will never be much longer than one wave length (on this length there are already two maxima and two minima), it will also be true for αy that $\alpha y \ll 2\pi$. Closer investigation of the value of α shows that this quantity is even so small that there is no objection to setting $2\alpha y \ll 1$, and thus $e^{2\alpha y}$ will be only slightly larger than 1.

Upon working out equation (21) further it is now found that the position of the voltage minima, as well as the variation of the voltage in the vicinity of these minima, is in the first approximation not affected by α, so that sufficiently accurate results for practical purposes are obtained when the losses of the Lecher system are disregarded.

Practical arrangement

The voltage variation along the Lecher system is measured with a diode voltmeter. The diode is placed in a holder which can be slid along the two conductors. It may often be of advantage to construct each of the two conductors of the system in two parts separated from each other by a thin insulating layer (see *fig. 3*). The capacity between these two parts of conductor is so large that with respect to high-frequency voltage they behave as one conductor. In this way the heating current can be supplied to the diode without wires being necessary to the diode. The circuit used for that purpose is represented in fig. 3. Between part b of conductor I and part a of conductor II a D.C. voltage occurs which is practically equal to the amplitude of the high-frequency voltage at the

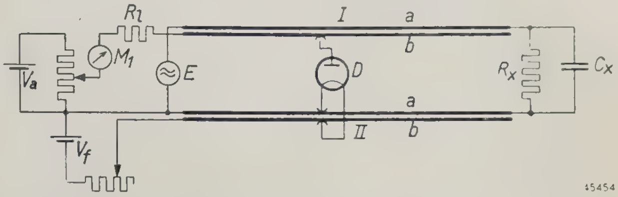


Fig. 3. The two conductors I and II of the Lecher system each consist of two mutually insulated parts a and b. E is the source of high-frequency voltage, V_f is the battery which furnishes the heating current of the diode, while V_a represents à battery by means of which the anode of the diode can be given a small negative bias. M_1 is a micro-ammeter in series with a leak resistance R_1.

point at which the diode is situated. The D.C. voltage can be measured at the beginning of the Lecher system by means of the galvanometer M_1, in series with which the resistance R_1 is connected. Thus no wires to the diode are needed for this either.

When the impedance to be measured is conductive for direct current [4]) it is preferably connected with part a of conductor I; this prevents interference of the measurement of the above-mentioned D.C. voltage by the impedance to be determined.

Errors of measurement

A disturbing element which often causes errors in measurement is the capacity of the measuring diode and of the diode holder. We desire, of course, to know the variation of the voltage along the Lecher system when it is completely "free" between the source of voltage and the impedance to be measured. It is only in that case that the above formulae are valid. Although in the development of the diodes used for these measurements and in the construction of the diode holder every effort was made to keep the capacity as small as possible, it cannot be reduced to such an extent that the Lecher system may be considered as being without load at the position of the diode. The result is that the high frequency voltage on the system is also affected by the location of the diode. It can be shown by calculation that the voltage which is measured in this case upon sliding the diode no longer varies symme-

[4]) The fact that the impedance to be measured can be represented by the connection in parallel of R_x and C_x does not mean that the object to be measured is conductive for direct current. R_x and C_x form only a diagram which has the same impedance as the required object at the frequency in question. Thus for example: the input impedance of a radio valve can be represented by a connection in parallel of a resistance and a capacity, while, nevertheless, practically no direct current conductivity exists between grid and cathode.

trically with respect to the maxima and minima as indicated in fig. 2*b*, but that it exhibits an unsymmetrical character, as shown for instance in *fig. 4*. The voltage read off at one side of a voltage minimum is too high and the other side too low. When the

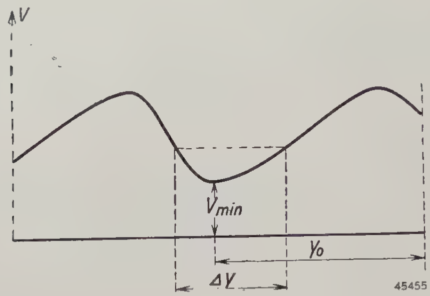


Fig. 4. Under the influence of the capacity of diode and diode holder the curve of the voltage becomes unsymmetrical with respect to the maxima and minima.

dissymmetry in the voltage curve measured is not too great and, moreover, Δy is small compared with the wave length, the deviations at either side of a voltage minimum approximately cancel each other and good measuring results are still obtained. When, however, Z_x differs only slightly from the wave resistance, the condition $\Delta y \ll \lambda$ is not satisfied for $V/V_{\min} = \sqrt{2}$, and incorrect results may be obtained. It is then necessary to eliminate the disturbing influence of the capacity of the diode and its holder. This can be done by introducing in parallel with the diode D a self-induction L_d (see *fig. 5*) which is made so large as to be in resonance

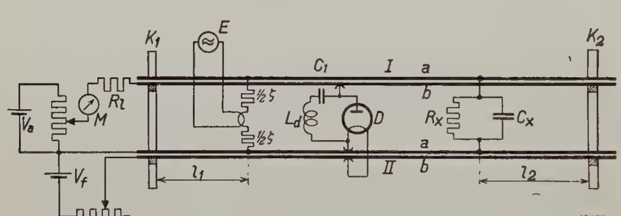


Fig. 5. The capacity of diode D and diode holder is tuned with the help of the self-induction L_d. C_1 is a blocking condenser for *DC* voltage. The source of high-frequency voltage E is coupled inductively with a loop connected with the Lecher system by means of two resistances which together are equal to the characteristic resistance ζ. K_1 and K_2 are short-circuiting bridges which short-circuit parts a of conductors I and II. The distance l_1 is so adjusted that the capacity of the resistances $^1/_2\zeta$ and of any holder for these resistances is compensated. By adjusting K_2 at the correct distance l_2 it is possible to compensate for the capacity of a holder in which the impedance to be measured is contained.

with the capacity of diode and holder, which can be ascertained from the fact that the voltage curve measured again becomes symmetrical with respect to the maxima and minima. The parallel circuit thus formed then represents a high impedance for the measuring frequency and has practically no effect on the shape of the voltage curve along the Lecher system.

Another possibility of reducing the effect of the diode capacity is to couple the diode with the system *via* very small capacities. One objection to this, however, is that a much higher high-frequency voltage is then necessary on the Lecher system. For many measurements this is of no importance, but for others there are very valid objections. Thus in measuring the input impedance of receiving valves the aim is to carry out the measurements as far as possible under the conditions under which the valves are used in practice, thus, among other conditions, with a low signal voltage. It may therefore be undesirable in this case to couple the measuring diode very loosely with the Lecher system.

In many cases the disturbing influence of the capacity of diode and holder can be reduced in yet another way, namely by constructing the source of voltage connected with the Lecher system in such a manner that it exhibits an internal resistance equal to the characteristic resistance. The resulting improvement can be explained from the fact that a voltage wave reflected at the diode cannot be reflected anew at the end where the source of voltage is situated. Whether or not this exerts a favourable effect on the above-mentioned measuring errors depends, however, upon various circumstances, for instance on the total length of the Lecher system. This should be investigated for each case individually.

Fig. 5 shows how in practice a voltage source with the desired internal resistance is obtained. The high-frequency voltage source E is inductively coupled with a loop, in series with which are two resistances ζ. These two resistances are connected with the Lecher system. As may be seen in fig. 5, the Lecher system is extended a certain distance to the left of this point of connection. On this part of the system we have the sliding short-circuiting bridge K_1 which short-circuits the parts a of the two conductors. This is done for two reasons. In the first place by setting K_1 at a certain distance l_1 the capacity of the above-mentioned resistances as well as that of a holder in which they are usually fastened can be compensated. Since the wave resistance of a Lecher system is practically a pure resistance, the internal impedance of transmitter, coupling loop and the above-mentioned resistances of $1/2\zeta$ should also be a pure resistance. The second purpose of the short-circuiting bridge K_1 is that it is possible to manipulate with the D.C. voltage connections to the left of it without affecting the distribution of high-frequency voltage on the Lecher

system. The system is also extended a certain distance to the right of the impedance to be measured. There is also a sliding short-circuiting bridge K_2 situated on this part of the system, which likewise short-circuits parts a. By setting K_2 at a certain l_2 it is possible to compensate for any capacity that may be in parallel with the impedance to be measured, for instance the capacity of a holder in which the object to be investigated is fastened and the capacity of an insulator support at this point.

at other places than at a minimum is less important the more precisely the above-mentioned precautions have been taken for reducing the disturbing effects of the capacity of diode and holder.

Another source of errors in measurement which we should like to mention is a possible mutual induction between the conductors of the Lecher system and the connections of those conductors with the measuring diode. It has been found that large errors may also result from this cause, especially in determining the position of a voltage minimum,

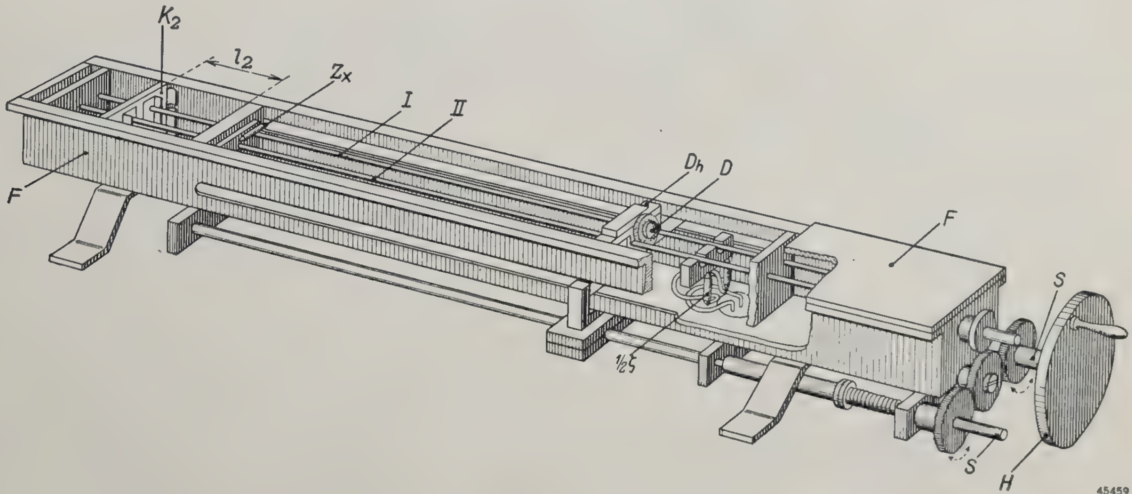


Fig. 6. Sketch of a measuring arrangement for impedance on decimetre waves according to the principle described in this article. In the drawing the cover and part of the wall of the housing F have been removed. The diode holder Dh is moved by means of the screw rods S which are driven by the hand wheel H. For the meaning of the other symbols refer to figs. 3 and 5.

The disturbing effect experienced from the capacity of the diode and its holder is greater in the neighbourhood of a voltage maximum than in that of a voltage minimum. This is due to the fact that the ratio between the voltage V and the current I is larger at a voltage maximum than at a voltage minimum. For that reason the first of the above-described methods of determining the modulus of f is carried out by measuring the voltage in the neighbourhood of a minimum, although in principle it would also be possible to measure the voltage in the neighbourhood of a maximum. For the same reason the second method of determining $|f|$ is only to be recommended when the shape of the voltage curve is such that there is little difference between a maximum and a minimum, *i.e.* when the impedance to be measured deviates only little from the characteristic resistance [5]). Of course the objection mentioned against measuring the voltage

[5]) If the impedance to be measured is equal to the characteristic resistance, no standing waves occur along the Lecher system, but only travelling waves. The same voltage is then measured at all points.

thus in the determination of the argument of the reflection factor f. These connections should therefore be kept as short as possible and should as far as possible run perpendicular to the two conductors of the Lecher system.

Fig. 6 is a sketch of a Lecher system used for measurements on the above-described principle. The Lecher system is contained in a housing F, the cover of which is partly removed in the drawing. The diode holder Dh, which is made of polystyrene, is moved along the conductors by means of screw rods S mounted outside the housing.

Diagram for calculation

When the modulus and the argument of the reflection factor f have been determined by the method described above, the impedance Z_x has to be calculated from those values by means of the expression (11a). This calculation proves to be rather laborious. It can be considerably shortened by the use of a diagram, an example of which is given in *fig. 7*.

The construction of this figure is based upon the

fact that Z_x is again determined by the connection in parallel of a resistance R_x and a loss-free capacity C_x or self-induction L_x. The real part of f is now plotted as abscissa and the imaginary part as ordinate, while the geometrical positions of f are drawn for certain fixed values of R_x/ζ and of $1/\omega C_x\zeta$ or $\omega L_x/\zeta$, respectively. These geometrical positions are found to be circles. Since the modulus of f is always smaller than 1, the whole diagram falls inside a circle of radius 1. Thus by plotting the measured modulus and the measured argument of f in this diagram the corresponding ratio of the resistance part and the reactive part of Z_x to the wave resistance ζ can be read off. By the use of these quantities without dimensions the diagram can be employed for a Lecher system with any characteristic resistance.

It is clear from fig. 7 that the method described is especially suitable for the measurement of impedances having a resistance component R_x lying between about 10ζ and $\zeta/10$.

For $R_x/\zeta>10$ and $R_x/\zeta<1/10$, the circles for successive values of R_x/ζ lie very close together, *i.e.* a small variation in f corresponds to a large change in R_x. The determination of R_x from f outside the limits mentioned above is therefore inaccurate. The method of measurement described in this article is thus a satisfactory complement to the article cited [1]), since the latter possesses a higher precision just outside the limits mentioned.

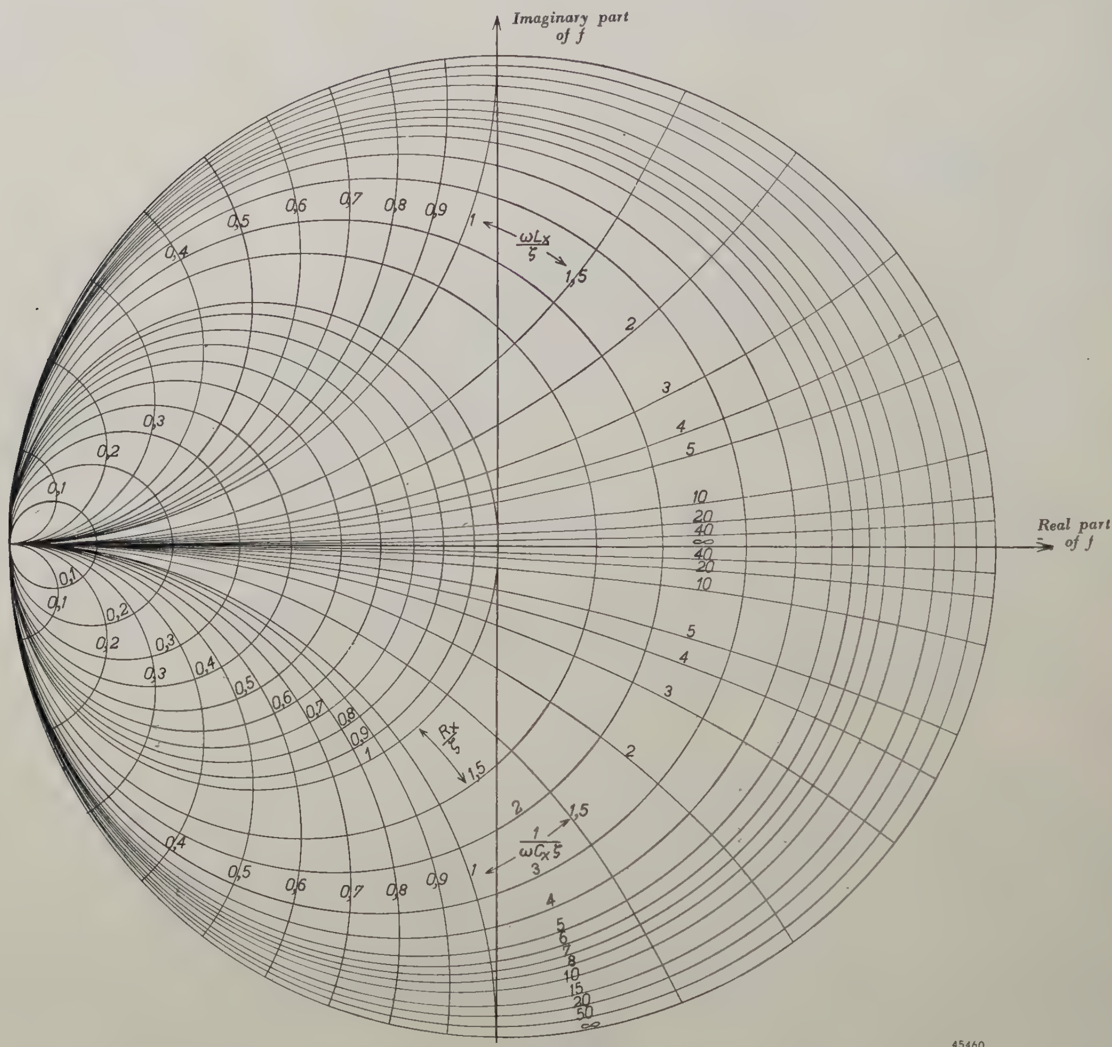


Fig. 7. Diagram for the determination of R_x and C_x (or L_x) from a measured value of the reflection factor f. The whole diagram falls inside a circle of radius 1.

Absolute values of the desired impedances

In the previous method as well as in the one described above the impedances to be measured are not found in absolute values, but only their ratios to the characteristic resistance. In order to determine the absolute value we must know the characteristic resistance. For simple constructions it can easily

be calculated. The necessary formulae are given below for two commonly used constructions.

For two parallel round wires of diameter d and at a distance a apart the characteristic resistance is

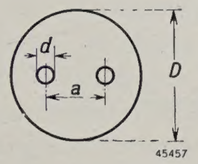
$$\zeta = 120 \ln (p + \sqrt{p^2-1}) \text{ ohm}, \quad . \quad (22)$$

in which

$$p = \frac{a}{d}.$$

If a cylindrical shield of diameter D is placed around these wires the characteristic resistance can also be calculated according to formula (23), but for p the following must be introduced:

$$p = \frac{a}{d} \frac{D^2-(a^2-d^2)}{D^2+(a^2-d^2)}.$$



A completely closed cylindrical shield cannot, however, usually be employed. For structural reasons a square cross-section is often used, while at the same time slits are often necessary in the shielding, for instance for the purpose of moving the diode holder (see fig. 6). Since a precise calculation of the characteristic resistance in such cases is complicated and often impossible, it is usually simpler to measure it. For that purpose it is sufficient to measure the capacity between the two conductors, which may be done at a low frequency [6]). If this capacity per cm is C^I farad and the self-induction of the Lecher system per cm is L^I henry the following relation exists between L^I and C^I:

$$L^I \cdot C^I = 1/c^2, \quad . \quad . \quad . \quad . \quad . \quad . \quad (23)$$

where c is the velocity of light in cm/sec, *i.e.* $c = 3 \times 10^{10}$. This formula holds for shielded as well as for non-shielded Lecher systems.

If C^I is now measured, the characteristic resistance ζ can be calculated from it, since it is given by:

$$\zeta = \sqrt{\frac{L^I}{C^I}} = \frac{1}{cC^I} \text{ ohm} \quad . \quad . \quad . \quad (24)$$

Measurement of impedance without a calibrated instrument

As will have appeared from the above description, in this method of measurement also a diode voltmeter is needed which is only relatively calibrated. Such a calibration is usually performed at a low frequency, namely by comparison with a thermocouple which in turn has been calibrated with direct current. As already stated in the article referred to [1]), at very high frequencies a calibration performed at a low frequency is, relatively, no longer correct either, due to the fact that the electrons in a diode possess a finite transit time. We shall therefore in conclusion give a brief description of a method by which it is possible to measure impedances on decimetre waves without a calibrated measuring instrument being necessary.

This method shows much similarity to the method described in this article. Here also the impedance to be measured is connected to the end of a Lecher system I, while the high frequency voltage source is connected with the other end. In addition to the measuring diode, however, a second Lecher system II can now also be moved along system I (see *fig. 8*).

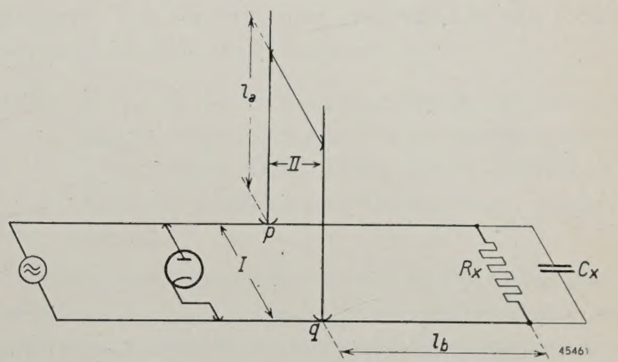


Fig. 8. Diagram showing the principle of an arrangement for measuring impedances on decimetre waves for which a calibrated voltage meter is not necessary. Lecher system II, which is provided with a moveable short-circuiting bridge, can be moved along Lecher system I. From the lengths l_a and l_b it is possible to calculate R_x and C_x.

System II is provided with a moveable short-circuiting bridge. It can be shown by calculation that at every value of R_x and C_x it is possible to adjust the length l_b so that the part of I lying to the right of II shows an admittance between p and q, the resistance component of which is equal to $1/\zeta$. The reactive component of this admittance can now be compensated by a suitable value of the length l_a. In this case, therefore, the part of I lying to the left of II is terminated by its own characteristic resistances and no standing waves occur along it. Upon moving the diode along the left-hand part of I no variation in voltage will then be observed. Z_x can now be calculated from the lengths l_a and l_b. We shall only give here the formulae to be employed for the case where the characteristic

[6]) When each of the conductors consists of a part a and b (figs. 3 and 5), those parts should of course be short-circuited.

resistance of systems *I* and *II* are the same. For modulus and argument of f the following are then valid:

$$|f| = \frac{1}{\sqrt{1 + 4\,\mathrm{tg}^2 2\pi \dfrac{l_a}{\lambda}}} \quad . \ . \ . \ . \quad (25)$$

and

$$\varphi = \mathrm{bg}\cos|f| - 4\pi\, l_b/\lambda \ . \ . \ . \ . \ . \quad (26)$$

From $|f|$ and φ we can now again calculate R_x and C_x (or L_x), using by preference a diagram like that of fig. 7.

Since in this method the diode voltmeter is only used to ascertain whether or not stationary waves are present on the Lecher system, it need not be calibrated at all. On the other hand it should be possible for the mechanism for adjusting the lengths l_a and l_b to be set with great precision.

The last issue of *Philips Research Reports* (No. 4 of volume 1, August 1946) contains the following papers:

R18: H. A. Klasens: Measurement and calculation of unsharpness combinations in X-ray photography.

R19: C. J. Bouwkamp: A contribution to the theory of acoustic radiation.

R20: M. Gevers: The relation between the power factor and the temperature coefficient of the dielectric constant of solid dielectrics II, III.

R21: J. Th. G. Overbeek: On Smoluchowski's equation for the electrophoresis of colloidal particles.

Readers interested in one of the above mentioned articles may apply to the Administration of the Philips Physical Laboratory, Kastanjelaan Eindhoven, where a limited numbers of copies are available for distribution. For a subscription to Philips Research Reports please write to the publishers of Philips Technical Review.

ABSTRACTS OF RECENT SCIENTIFIC PUBLICATIONS OF THE N.V. PHILIPS' GLOEILAMPENFABRIEKEN

Reprints of the majority of these papers can be obtained on application to the Administration of the Research Laboratory, Kastanjelaan, Eindhoven, Netherlands. Those papers of which no reprints are available in sufficient number, are marked with an asterisk.

1683: H. Rinia and P. M. van Alphen: A new method of producing aspherical optical surfaces (Proc. Kon. Ned. Akad. Wetenschappen, Amsterdam **49**, 146-149, 1946).

Descartes and Newton already advocated the use of aspherical surfaces in optical instruments. Recently interest in these has increased in connection with Schmidt's mirror system. Apart from field curvature this system has only one aberration, *viz.* spherical aberration, which can be eliminated by using a correction plate with a 4th degree surface. The manufacturing of these surfaces in mass production by grinding or pressing encounters many difficulties. In this article a method is described, by which the plates are cast from a gelatin solution. Some experiments with lenses provided with this aspherical gelatin surface likewise yielded good results.

1684: H. Rinia: New possibilities for the air engine (Proc. Kon. Akad. Wetenschappen, Amsterdam **49**, 150-155, 1946).

After surveying the different types of caloric engines the author describes the principle of the air engine. A favourable temperature ratio, a satisfactory heat transfer and adequate regeneration are the requirements to be fulfilled. Thanks to improvements it has become possible to construct engines working at 3000 rpm at a mean pressure of 10 atm. with an overall output exceeding that of petrol engines.

1685: P. J. Bouma: Zur Einteilung des Ostwald'schen Farbtonkreises (Experientia **2**, 99-103, 1946).

The author demonstrates that the „principle of inner symmetry", used by Ostwald as a basis for his colour circle, contains a number of contradictory requirements. After restriction of the principle it proves possible to compute the dominant wavelengths of the 24 colour points of the Ostwald circle situated on the curve of the characteristic colours in the colour triangle. The results of these calculations are compared to the data of Richter.

1686: J. van Slooten: Meetkundige beschouwingen in verband met de theorie der electrische vierpolen (thesis Delft 1946) (Geometrical considerations in connection with the theory of electric four terminal networks).

The theory treated in this thesis consists of two parts: the first two chapters deal with the properties of fourpoles as impedance transformers. In the last three chapters the question is raised how, when connecting in cascade (or in parallel) two fourpoles without losses, whose transformer properties are known, the properties of the resulting fourpoles may be found. It is proved that connection in cascade is equivalent to the addition of motions in non-euclidian space. This may be done in a so-called Cayley diagram worked out for this special purpose. The constructions are useful in the technique of ultra short radio waves.

1687: F. L. H. M. Stumpers: Eenige onderzoekingen over trillingen met frequentie-modulatie (thesis Delft 1946) (Some investigations an oscillations with frequency modulation).

In this thesis attention is paid to the definitions of instantaneous amplitude, phase and frequency as a function of time; the frequency spectrum occurring with different kinds of modulation is calculated and the possibility of interference with frequency modulated signals (*e.g.* by two emitters on one carrier wave, synchronised emitters or two-way reception) is studied.

The influence of noise and disturbances is thoroughly investigated. Whereas only approximative calculations are possible in the case where the noise energy is not small in comparison with the signal energy, in the case of impulse disturbances the calculations can be worked out completely.

The distortion suffered by frequency modulated signals in passing through the electrical network is calculated using Fourier analysis and the series of Carson and Fry. The methods used by these last named authors are critically studied and an alternative development is given, which is more adapted to the case of F.M., and which also has an asymptotic charecter. The theory is applied to simple networks: simple circuit, coupled circuit, frequency detector. Apart from the formation of harmonics intermodulation is considered.

Finally the results are checked by experiments. A new method for determining the distortion of the measuring emitter directly from the spectrum deserves attention.

1688: N. Warmoltz: Over het mechanisme van den capacitieven ontsteker en van den weerstand bij kwikdampgelijkrichters (thesis Delft 1946) (On the mechanism of dielectric-ignition and resistance ignition in mercury arc rectifiers).

A short survey is given of ignition methods in mercury pool rectifiers, based on the field theory of the low pressure mercury arc. The time lag of the dielectric ignitor is measured by oscillographic methods. It is in accordance with the spaces of time required for the rupture by an electric field of a small distortion on the mercury surface as computed by Tonks. The field strength at the sharp point, which is formed during this process, is sufficient for cold emission of electrons, from which an arc develops in the mercury vapour formed simultaneously.

As regards the behaviour of the time lag of resistance ignitors in experiments with frozen cathodes, preheating the ignitor, arguments are found in favour of Mierdel's theory on this subject.

1689: J. van der Vliet: De provitaminen-D van de mossel (mytilus edulis), thesis Groningen 1946 (The provitamines D of the mussel).

The mixture of provitamines D from the sterol fraction of the mussel is investigated. From the product obtained from this mixture by irradiation with ultraviolet rays a crystalline substance with antirachitic properties has been isolated (called D_x), which on closer examination proved to consist of a mixture of calciferol and an unknown antirachitic, almost inactive compound related to vitamine D, having the probable composition $C_{28}H_{44}O$ or $C_{29}H_{46}O$ and containing an unsaturated side branch. Further vitamine D_3 was isolated as a crystalline ester. Oxidation of the irradiation-product with ozone gave different new products, who where also identified. From chemical as well as biological data it is concluded that the composition of the provitamine mixture is:

7-dehydro-chloresterol	50%
ergosterol	17%
cholestatriene -5, 7, 22-ol-3	33%.

The presence of the two first mentioned compounds is proved, that of the last one made probable.

1690: N. H. W. Addink: Complete and incomplete crystals. (Nature **157**, 764, 1946).

The author presents a table containing which to his opinion are the most reliable values of N (Avogrado's number, chemical scale), calculated from the density and from the dimension, as measured by X-ray methods, of the elementary cell in the case of diamond, KCl, quartz, calcite, PbO, Sn and various other metals (partly from measurements by the author and coworkers).

It is seen that the value of N found increases in the order mentioned, corresponding to an increasing deviation from the ideal density. The term incomplete is proposed for crystals showing a density inferior to the ideal value. The value for 10^{-23} N is $6.0227^5 + .0003$ for diamond, which is very near to Birge's value of $6.02283 \pm .0011$.

1691: Balth. van der Pol: The fundamental principles of frequency modulation (J. Inst. El. Engineers **93**, 153-158, 1946).

In a lecture for the radio section of the I.E.E. the author treats:

1) the problem of finding the possible current and voltage in a circuit with *L*, *C*, *r* and condensor leak *R* being arbitrary functions of the time, and
2) the problem of the response of a given network to a frequency modulated signal. In addition the definitions of amplitude phase and frequency are discussed.

1692: A. Claassen and J. Visser. The determination of uranium with oxy-quinoline (Rec. Trav. Chim. Pays Bas **65**, 211-215, 1946).

The method of Hecht and Reich-Rohwig for the determination of U by means of O-oxy-quinoline has been subjected to a critical investigation. It was found that washing with a hot 0.04% oxine solution is to be preferred to washing with hot water. Results are accurate within 0.1%. Separation from Mg, alkaline earths and alkali metals is complete.